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BRIEF EXAMINATION OF THE POSSIBILITY FOR CONDENSATION TRAILS TO OCCUR ON PROJECTILES DUE TO AERO-THERMODYNAMIC CAUSES

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June 1982

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ABERDEEN PROVING GROUND, MARYLAND

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Test firings of an Army projectile carrying a liquid payload have resulted in sightings of a brief vapor trail early in the flight of the projectile. The purpose of this memorandum is to examine the possibility for aero-thermodynamics to generate a visible condensation trail behind a shell. Flow field computations using thin-layer Navier-Stokes computational techniques have been accomplished to define the local flow temperature distribution about a typical shell at M = .9 and M = 2. These results indicate that small regions of local flow exist that are conducive to produce condensation;

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however, these flow conditions are quickly modified by the presence of shock-boundary layer interactions and recompression. It is concluded that aero-thermodynamics is an unlikely cause of the reported projectile trails.

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I. INTRODUCTION

Test firings of an Army projectile carrying a liquid payload have resulted in sightings of a brief vapor trail early in the flight of the projectile. These sightings had an occurrence of about 19 in 80 at the most recent series of firings. The vapor trails occurred for projectiles preconditioned to 241K (435R) and 294K (530R). The atmospheric conditions varied from 278K (501R) to 294K (530R) with a typical relative humidity of 40%.

Several possible causes for the vapor trails have been postulated. The purpose of this memorandum is to examine the possibility of the external aerodynamic flow over projectiles causing vapor trails to be generated.

II. CONDENSATION PROCESS

The occurrence of condensation is possible when the local temperature is such that the vapor pressure is saturated (relative humidity of 100%). There are two types of condensation processes -- heterogeneous and homogeneous. Heterogeneous condensation occurs at the surface of foreign particles (such as atmospheric dust) which act as a catalyst. The resulting condensation occurs at low levels of supersaturation. Homogeneous condensation occurs in the absence of foreign particles. Since no catalyst is present, this type of condensation process proceeds at a relatively slow rate at high levels of supersaturation. The most likely condensation process for the projectile problem is heterogeneous nucleation. That is, condensation takes place on foreign particles such as dust particles in the atmosphere or on the projectile. This type of condensation occurs for near equilibrium conditions since the presence of the foreign particles act as catalysts.

Condensation occurs at a rate which is dependent upon many factors such as the density of foreign particles present, degree of supersaturation, size of particles, local temperature, local pressure, flow history, etc. Although the physics of the condensation process are well known, the prediction of the rate of condensation is subject to considerable uncertainty. Thus it is expedient and reasonable to proceed in this initial analysis by considering that it is possible for condensation to occur for local temperatures at or below the dew point temperature assuming thermodynamic equilibrium conditions.

III. POSSIBLE MECHANISMS

A. Overview.

Two possible mechanisms for generating a visible trail of the projectile due to aero-thermodynamic effects are: (1) local flow expansion over discontinuities in surface curvature such as occur at the ogive-cylinder and cylinder-boattail junctions for a projectile; and (2) formation of frost on a cold conditioned shell.

B. Local Flow Expansion.

A series of computations have been run at M = 0.90 and M = 2 for several free stream and wall temperature boundary conditions. The resulting flow fields have been examined to determine regions of static temperature distributions conducive to producing condensation in the air stream.

The computational techniques utilized are the thin-layer Navier-Stokes codes described in Reference 1 for the transonic velocity and in Reference 2 for the supersonic velocity.

The flow conditions examined are summarized in Table 1. The projectile is a six-caliber ogive-cylinder-boattail shape (Figure 1) which approximates the M549 projectile.

TABLE 1. FLOW FIELD CONDITIONS

M	T_∞	T_W	T_D	RH
.90	277 294	241 241, 294	266 280	40%
2.0	277 294	241 241, 294	266 280	40%

M - Mach number
T_∞ - free stream static temperature, °K
T_W - projectile wall temperature, °K
T_D - dew point temperature, °K (based on local RH at the test site)
RH - relative humidity

1. *Nietubicz, C.J., Pulliam, T.H., and Steger, J.L., "Numerical Solution of the Azimuthal-Invariant Thin-Layer Navier-Stokes Equations," U.S. Army Ballistic Research Laboratory/ARRADCOM Report ARBRL-TR-02227, Aberdeen Proving Ground, MD 21005, March 1980. AD A085716.*

2. *Schiff, L.B. and Sturek, W.B., "Numerical Simulation of Steady Supersonic Flow Over an Ogive-Cylinder-Boattail Body," U.S. Army Ballistic Research Laboratory/ARRADCOM Report ARBRL-TR-02363, Aberdeen Proving Ground, MD 21005, September 1981. AD A106060.*

Figure 2 is a static temperature contour plot for the transonic Mach number, M = 0.9. It shows the overall static temperature distribution about the projectile. Notice the low temperature region on the projectile boattail downstream of the expansions that occur at the cylinder-boattail junction.

Examples of the static temperature distributions are shown in Figures 3 through 14 for Mach number, M = 0.9.

Figures 3, 4 and 5 show examples of the longitudinal variation of stream temperature at a fixed distance from the model surface, Y/D = .0133 cal for different values of atmospheric temperatures. The extent of the regions where the temperature is less than the dew point is indicated and is less than 0.1 calibers. Note that the stream temperature quickly recovers to a value substantially greater than the dew point on the projectile boattail.

The variation of stream temperature perpendicular to the body axis at a fixed longitudinal station is shown in Figures 6-14. Again, the extent of the flow field at or below the dew point is indicated and is obviously quite small. The plots for X/D = 5.23 (Figures 12, 13, and 14) show that the static temperature has quickly reached a value significantly above the dew point shortly downstream of the beginning of the boattail.

An example of a contour plot of the static temperature distribution about the projectile at Mach = 2 is shown in Figure 15 for T_W = 241K (435R) and T_∞ = 277K (500R). This plot gives an overall perspective of the pockets of low temperature flow which exist downstream of the expansions occurring at the ogive-cylinder and cylinder-boattail junctions.

Examples of the static temperature distributions for the supersonic Mach number, M = 2, are shown in Figures 16 through 27.

The first series of plots, Figures 16, 17, and 18, show the longitudinal temperature distribution at a position above the projectile surface which is at or very near the minimum stream temperature. These plots indicate that there exists a region about one caliber in length over which the local stream temperature is sufficiently low to produce condensation.

The next series of plots, Figures 19, 20, and 21, show the temperature distribution above the model surface perpendicular to the axis at a longitudinal station upstream of the boattail. These plots indicate that the local temperature stays above the dew point.

The next series of plots, Figures 22, 23, and 24, show the temperature distribution just downstream of the start of the boattail -- very close to the position for minimum temperature. These plots indicate the existence of a very thin region in which the stream temperature is below the dew point.

The final series of plots, Figures 25, 26, and 27, show temperature distributions further downstream on the projectile boattail. Again, a very thin region is shown to exist where the stream temperature is below the dew point resulting from the flow expansion that occurs at the start of the projectile boattail.

Considering these results, it is concluded that any vapor condensed in the flow field over the projectile is quickly vaporized downstream of the shock over the boattail for the M = 0.9 case. Similarly for the M = 2 case, any vapor condensed in the flow over the boattail is either too small for observation or vaporized in the mixing and recompression that occurs in the projectile's near wake.

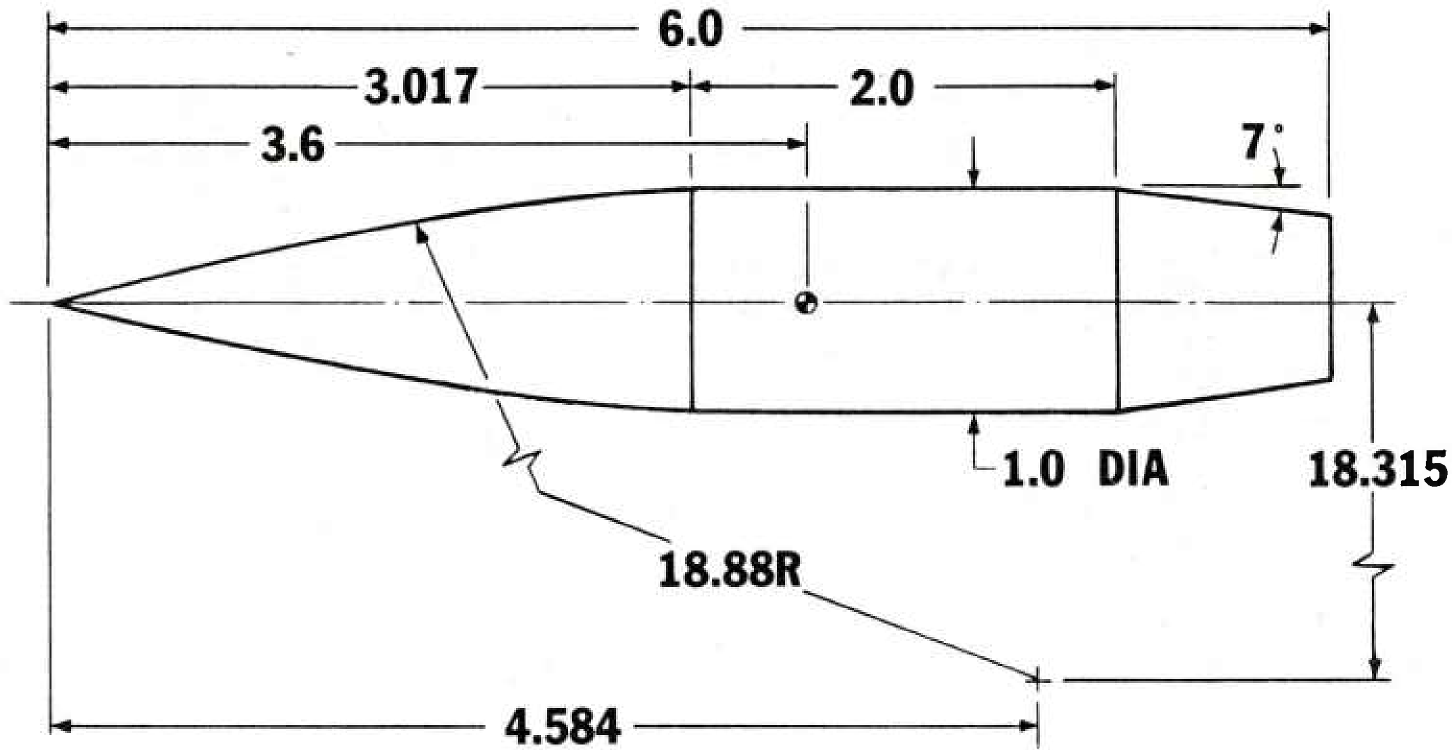
C. Frost Formation on Cold Projectile.

The cold conditioning temperature for the projectiles -- 241K (435R) -- is far below the dew temperature -- 266K (488R) and 280K (505R) for atmospheric temperatures of 277K (500R) and 294K (530R), respectively -- for the firing conditions of interest. Thus frost readily forms on the projectile. It is conceivable that frost would continue to form after the projectile is launched. Upon sufficient buildup of frost, it is also conceivable that the frost covering would dislodge and leave a trace similar to the reported sightings. However, this would only occur for cold conditioned projectiles. Since trails have also been observed for projectiles preconditioned to 294K (530R), it is unlikely that frost formation is the cause of the reported vapor trails.

IV. SUMMARY

The possible generation of a condensation trail behind an artillery shell has been examined by considering the local flow fields existing about a projectile at a transonic and a supersonic flight Mach number. The analysis has shown that the local flow about a projectile does contain regions in which the local static temperature is conducive to create condensation. However, these local flow conditions conducive to condensation are quickly altered in the recompression and mixing that occur in the vicinity of shocks over the projectile or near the base of the projectile. Thus, if condensation occurred in the external aerodynamic flow over the projectile, a very short lived trail would likely be observed over the full trajectory of the projectile's flight -- not merely the short burst signature observed shortly after launch for the projectile in question. It is also considered unlikely that frost formation is the cause of the reported projectile trails since sightings were observed for projectiles preconditioned to 294K (530R).

Thus, it is concluded that it is highly unlikely that external aerodynamics is the cause of the observed signature.



ALL DIMENSIONS IN CALIBERS
DIA = 2.25 inches

Figure 1. Model Geometry

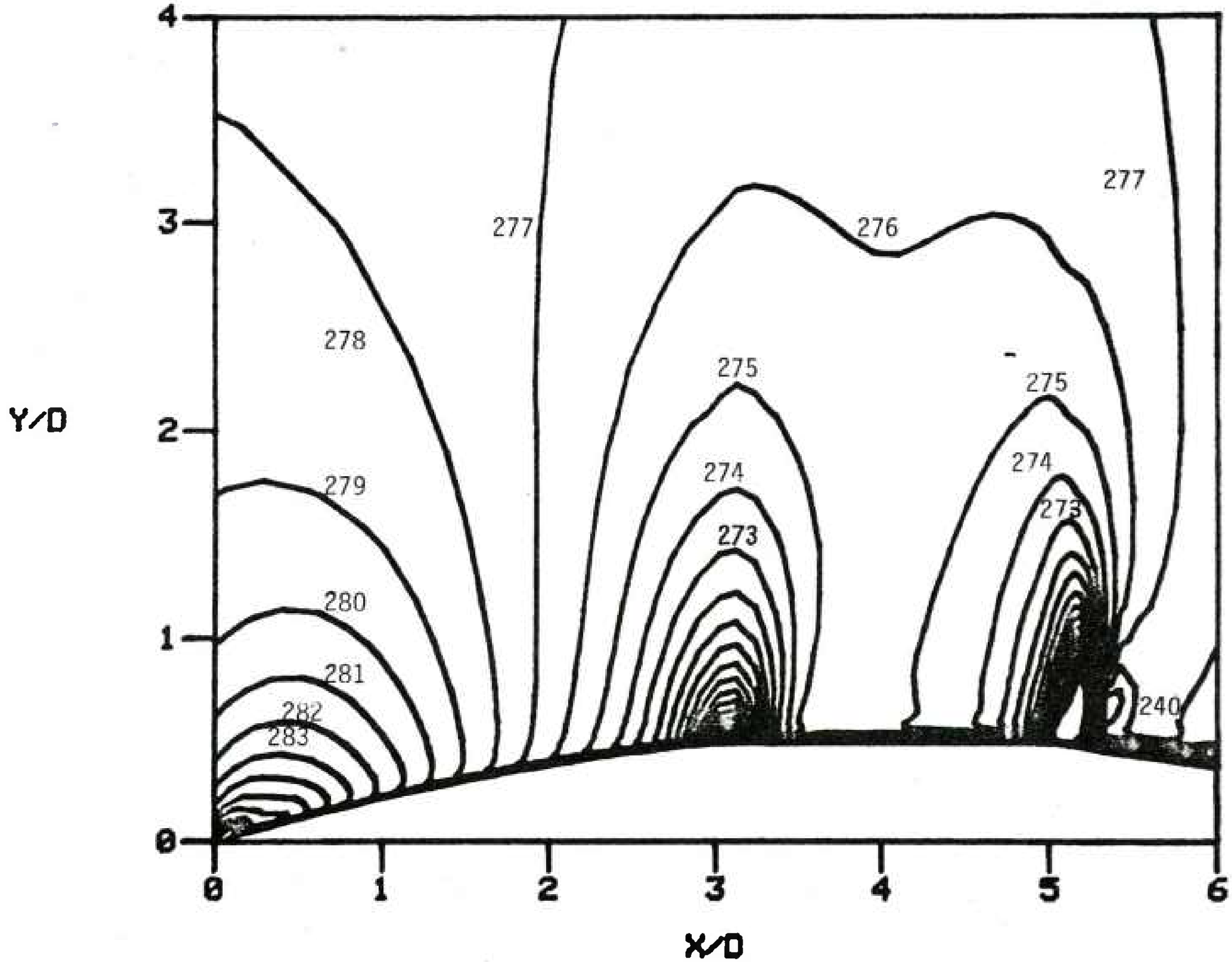


Figure 2. Static Temperature Contour Plot, $M = 0.9$, $T_\infty = 277K$, $T_W = 241K$, $T_D = 266K$

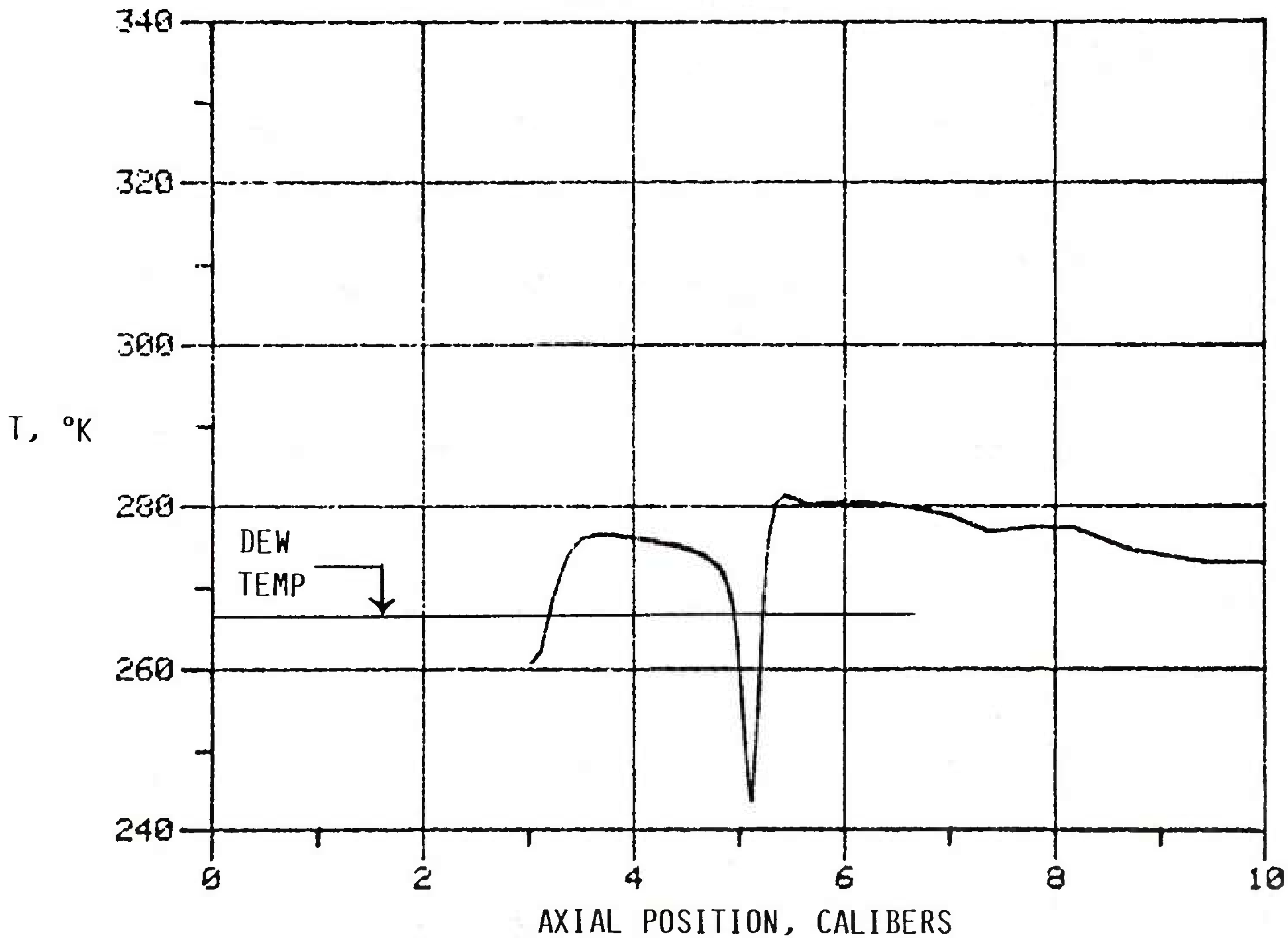


Figure 3. Longitudinal Temperature Distribution, $M = 0.9$, $T_{\infty} = 277K$, $T_W = 241K$, $Y/D \approx .0133$

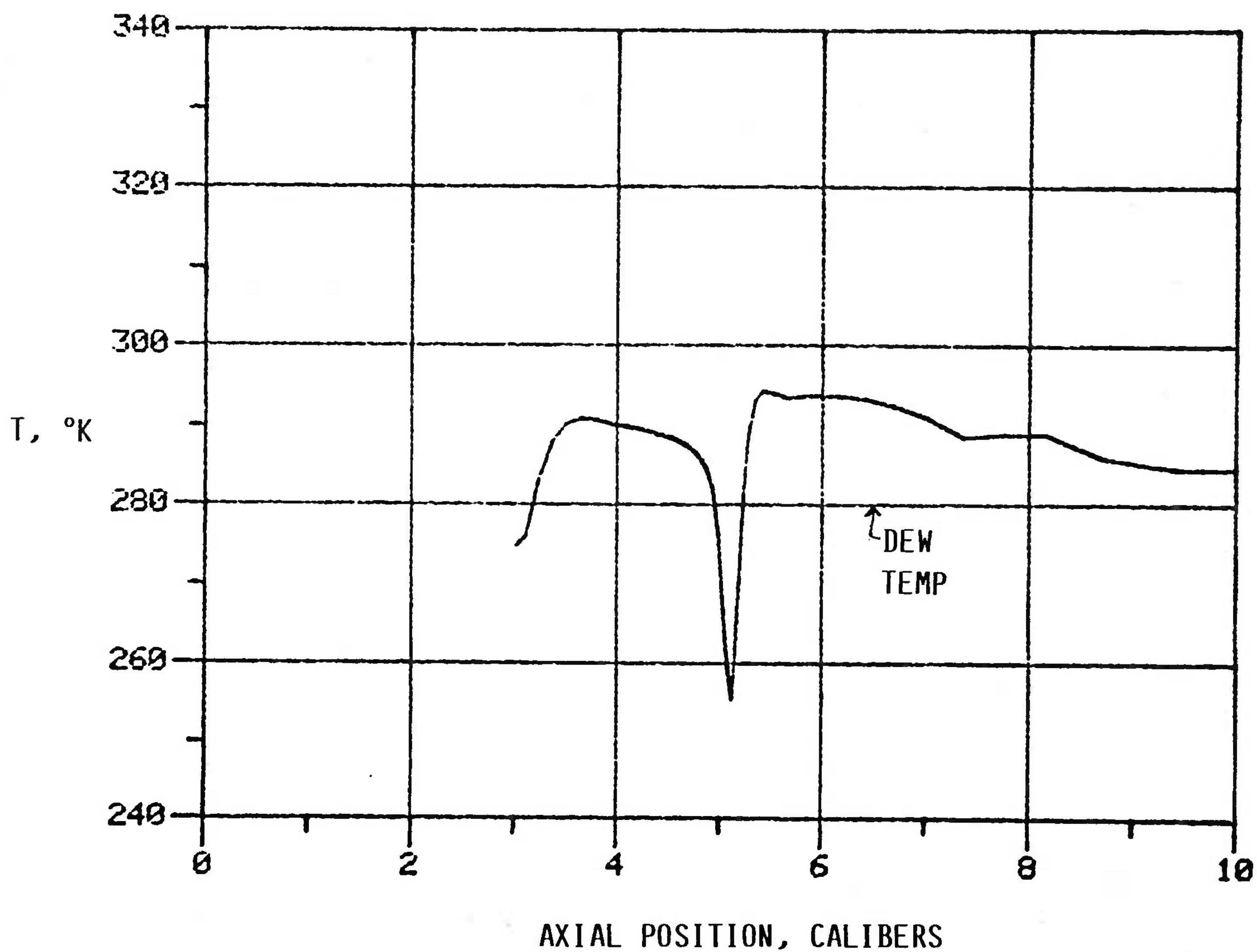


Figure 4. Longitudinal Temperature Distribution, M = 0.9, T_∞ = 294K, T_w = 241K, Y/D ≈ .0133

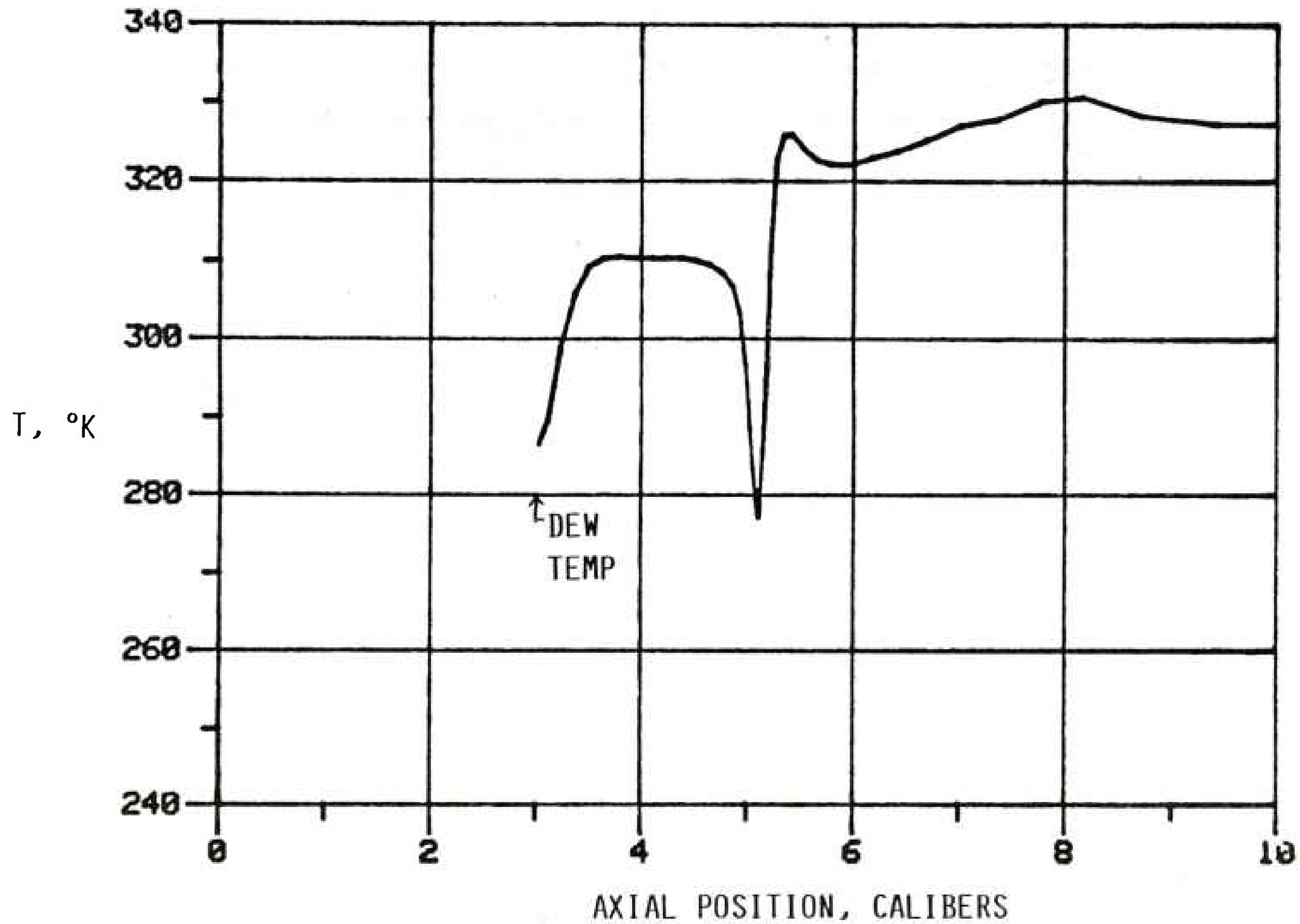


Figure 5. Longitudinal Temperature Distribution, M = 0.9, T_∞ = 294K, T_W = 294K, Y/D ≈ .0133

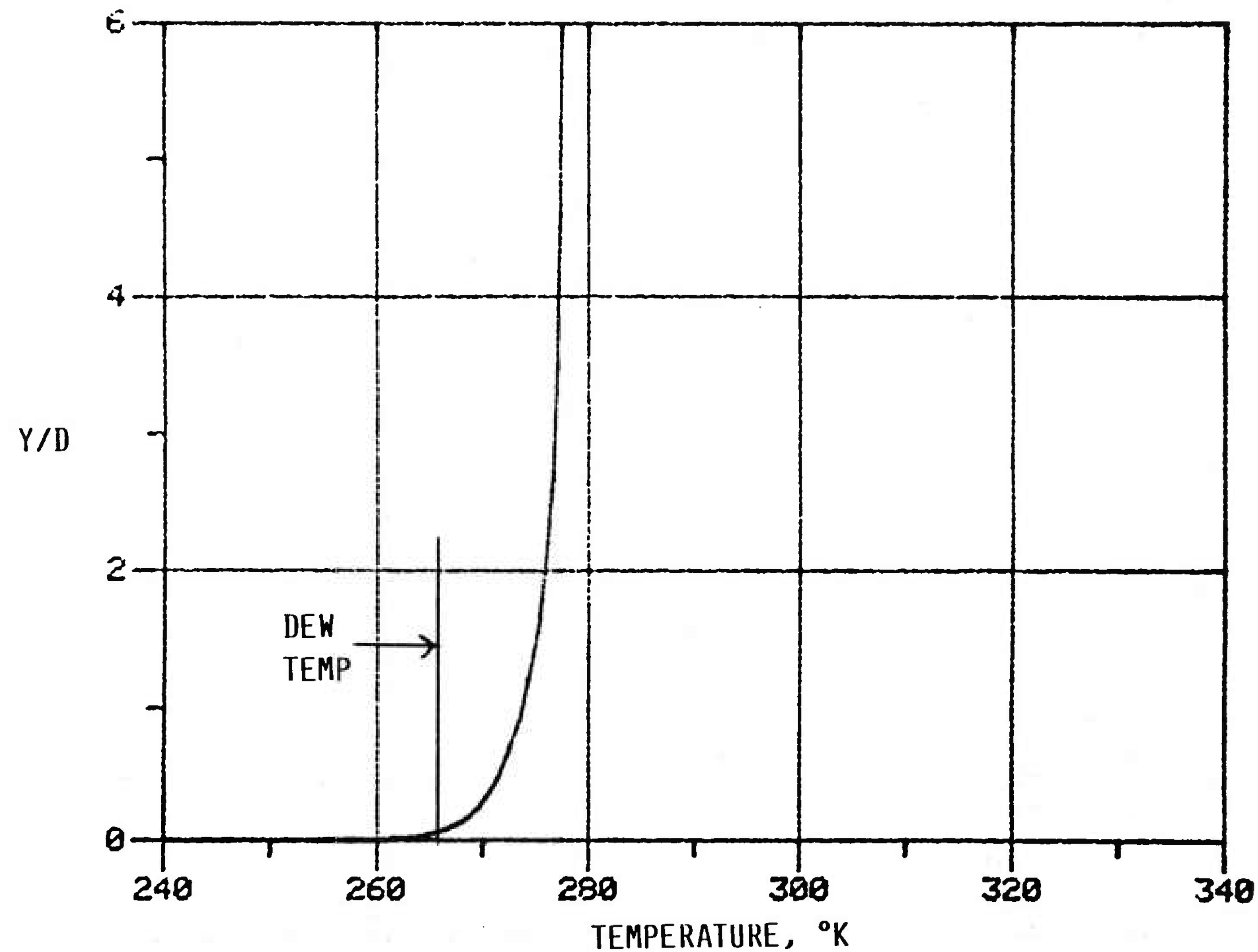


Figure 6. Temperature Profile, M = 0.9, T_∞ = 277K, T_w = 241K, X/D = 4.99

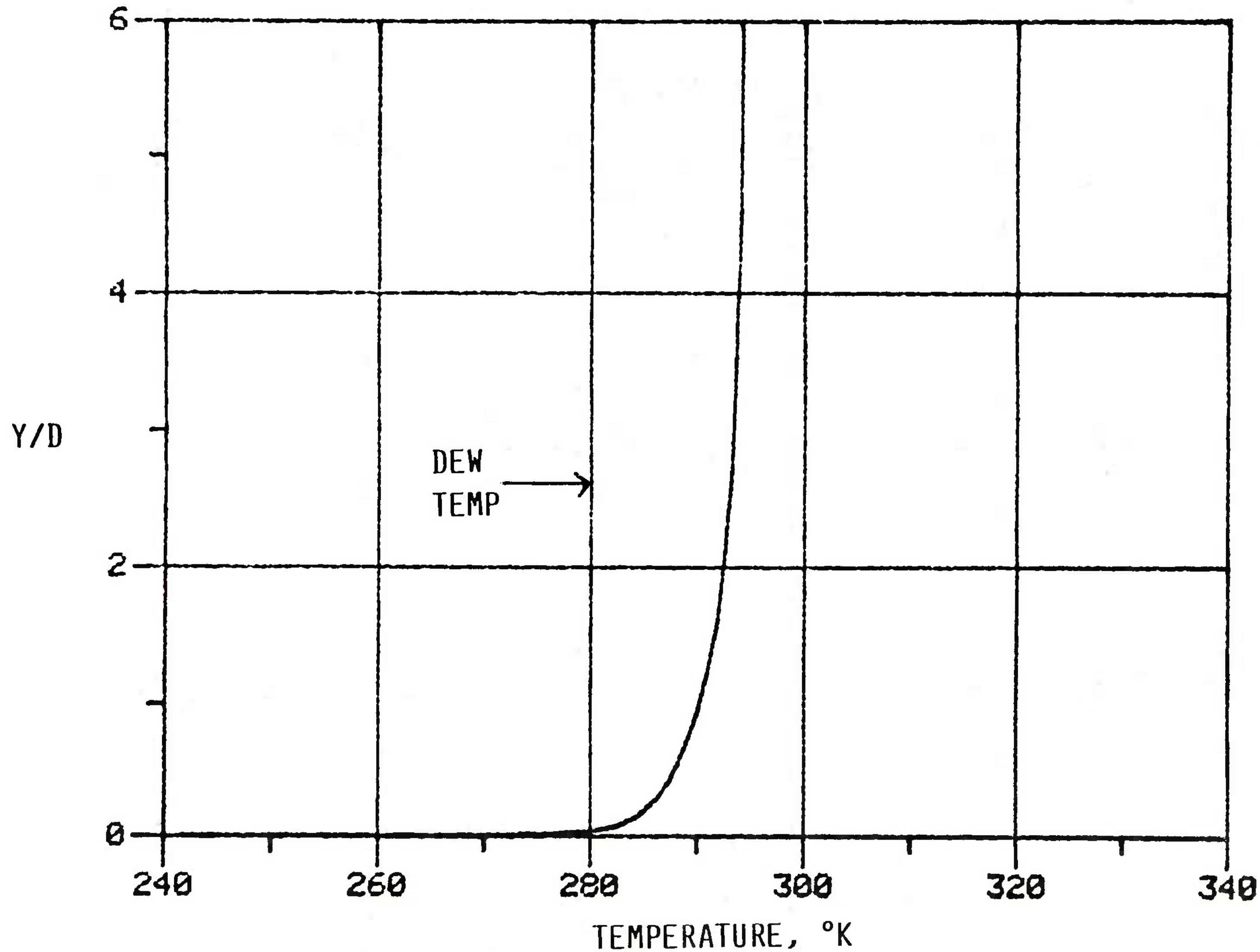


Figure 7. Temperature Profile, M = 0.9, T_∞ = 294K, T_W = 241K, X/D = 4.99

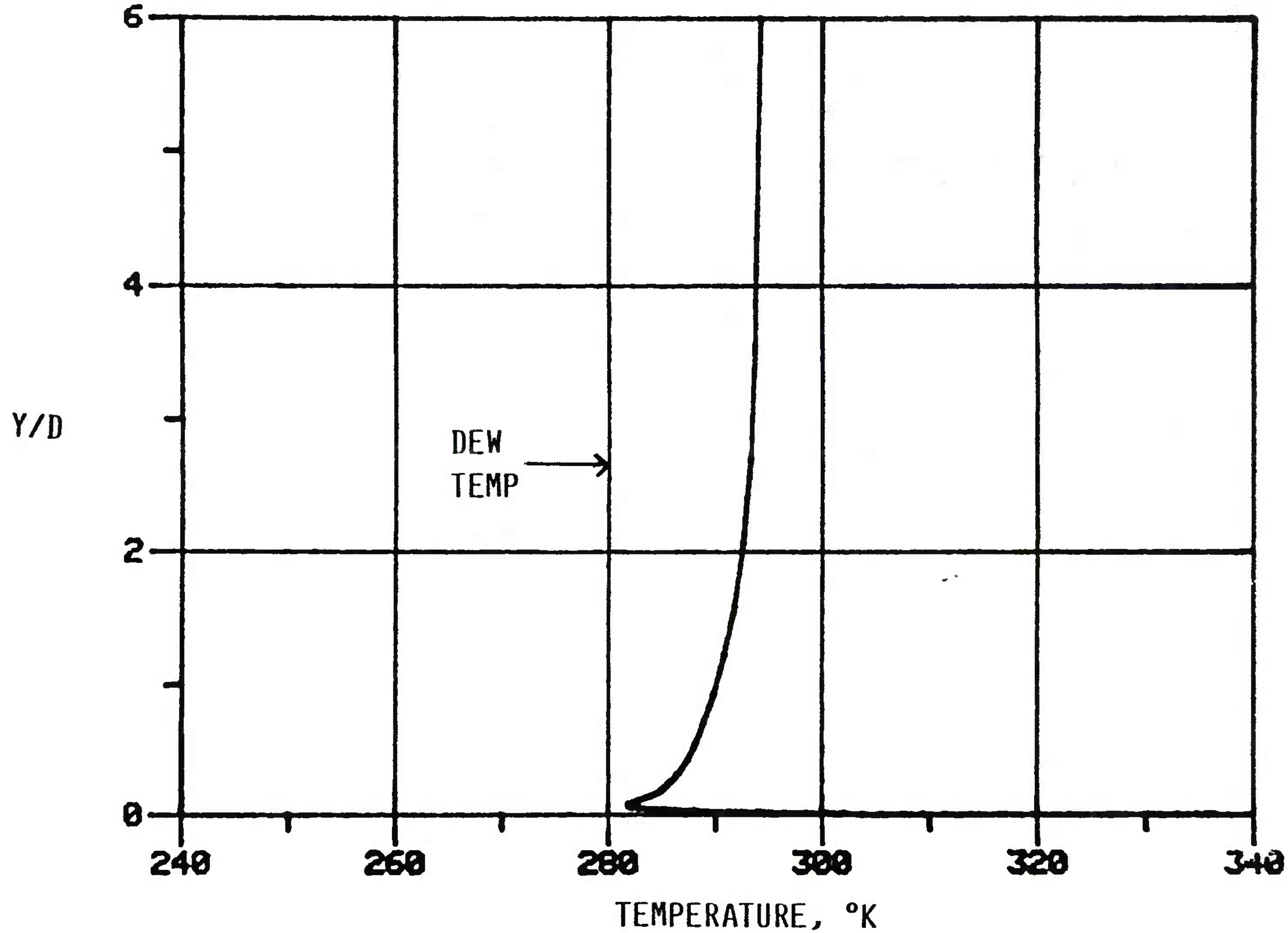


Figure 8. Temperature Profile, M = 0.9, T_∞ = 294K, T_w = 294K, X/D = 4.99

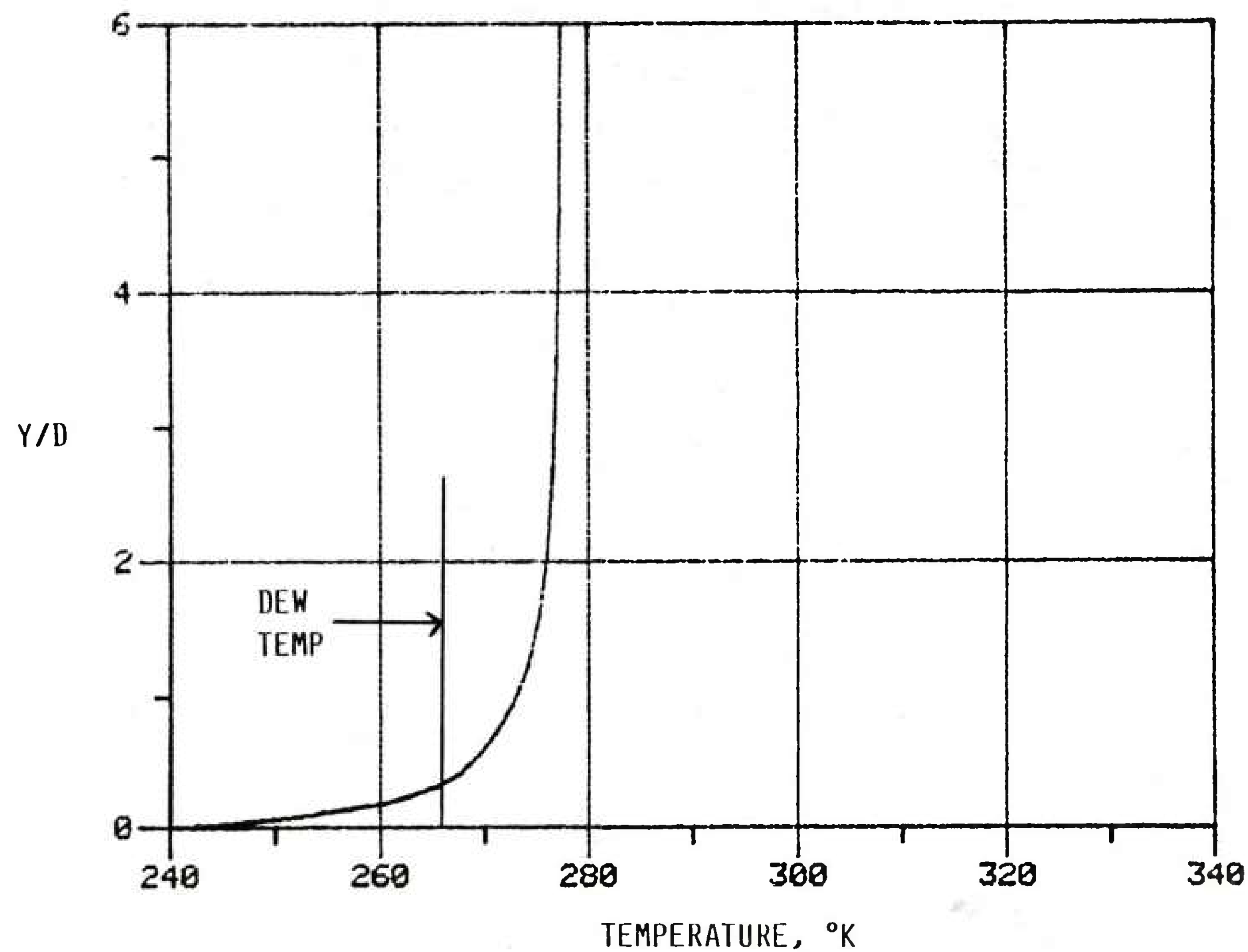


Figure 9. Temperature Profile, M = 0.9, T_∞ = 277K, T_W = 241K, X/D = 5.1

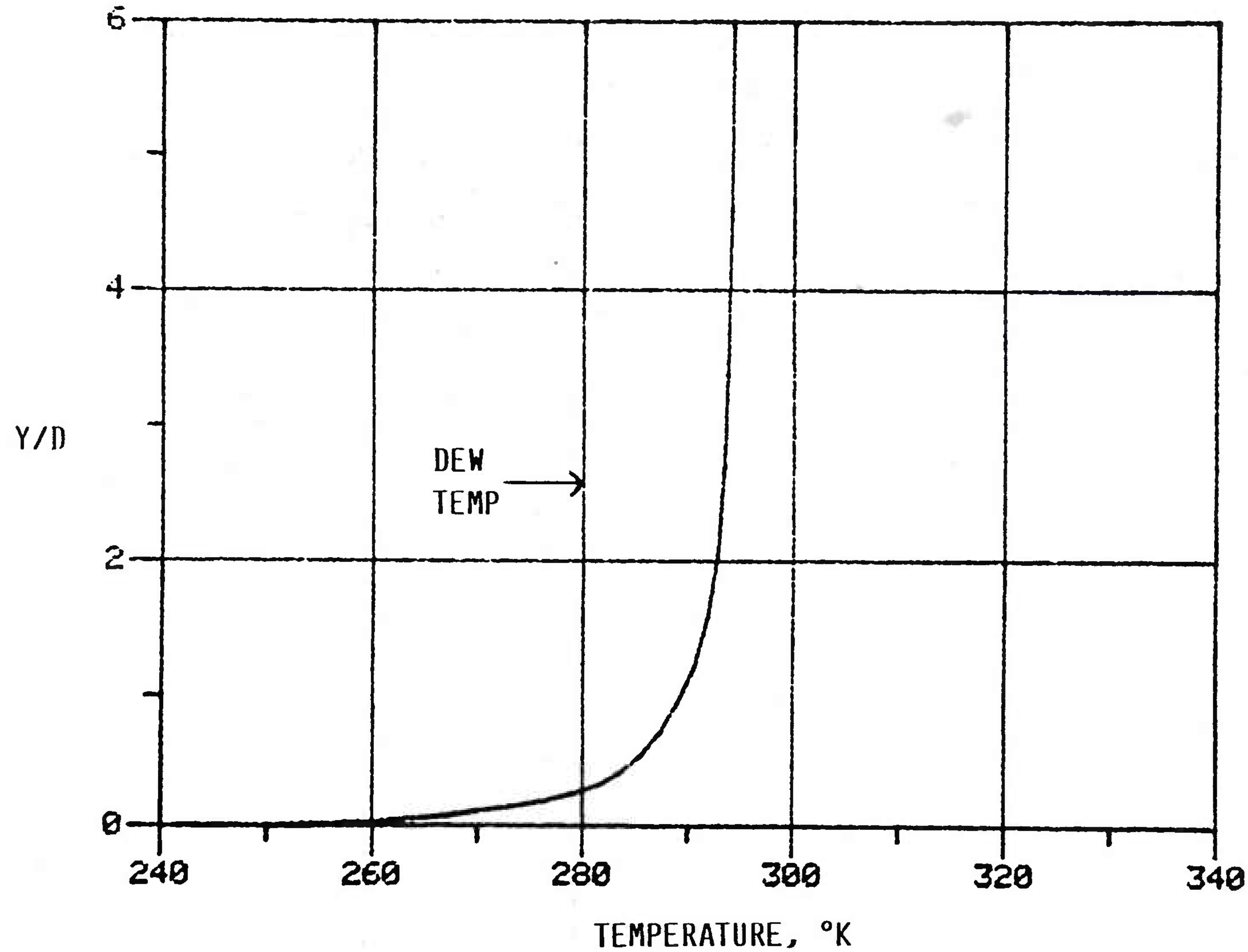


Figure 10. Temperature Profile, M = 0.9, T_∞ = 294K, T_W = 241K, X/D = 5.1

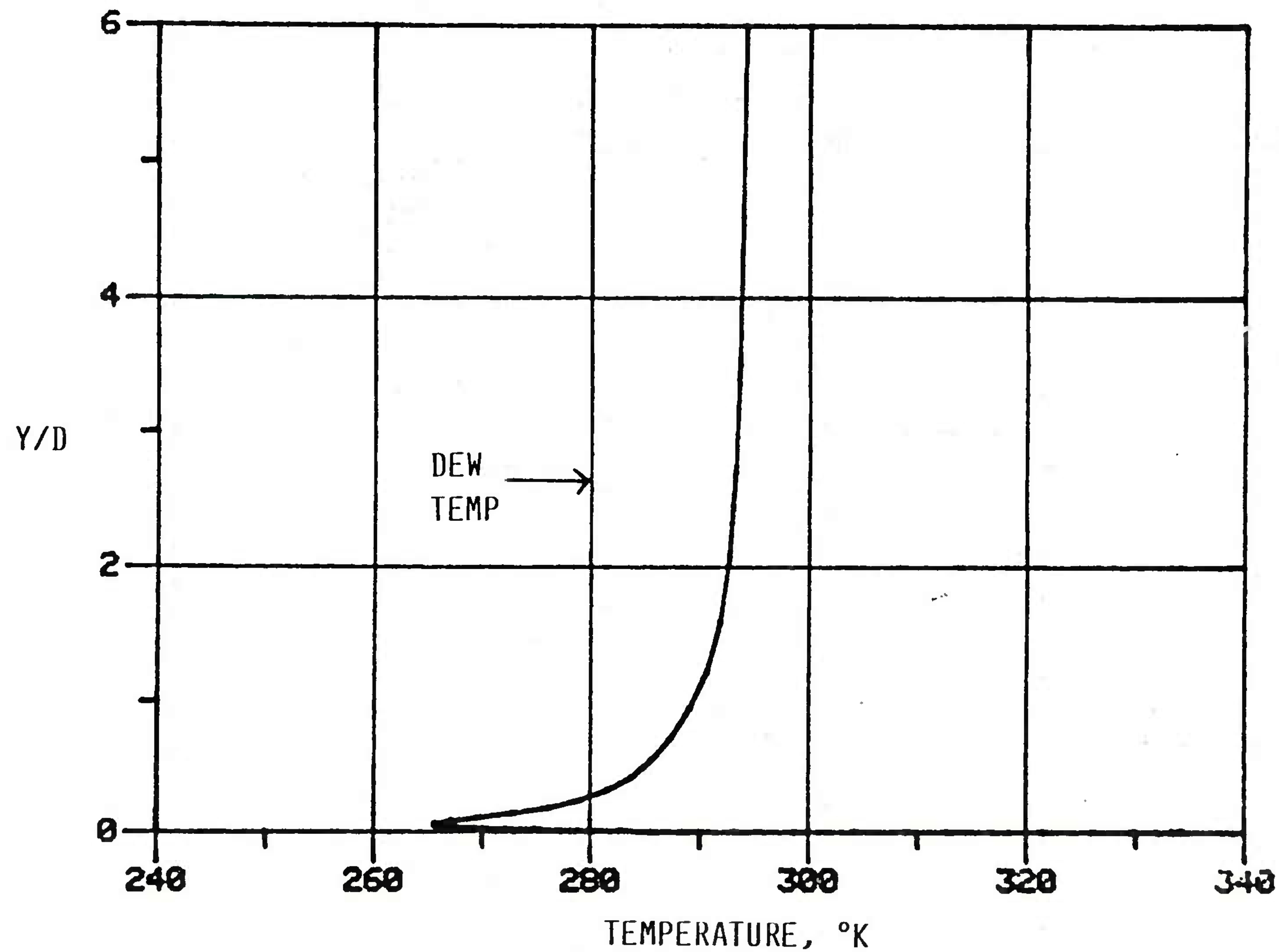


Figure 11. Temperature Profile, M = 0.9, T_∞ = 294K, T_W = 294K, X/D = 5.1

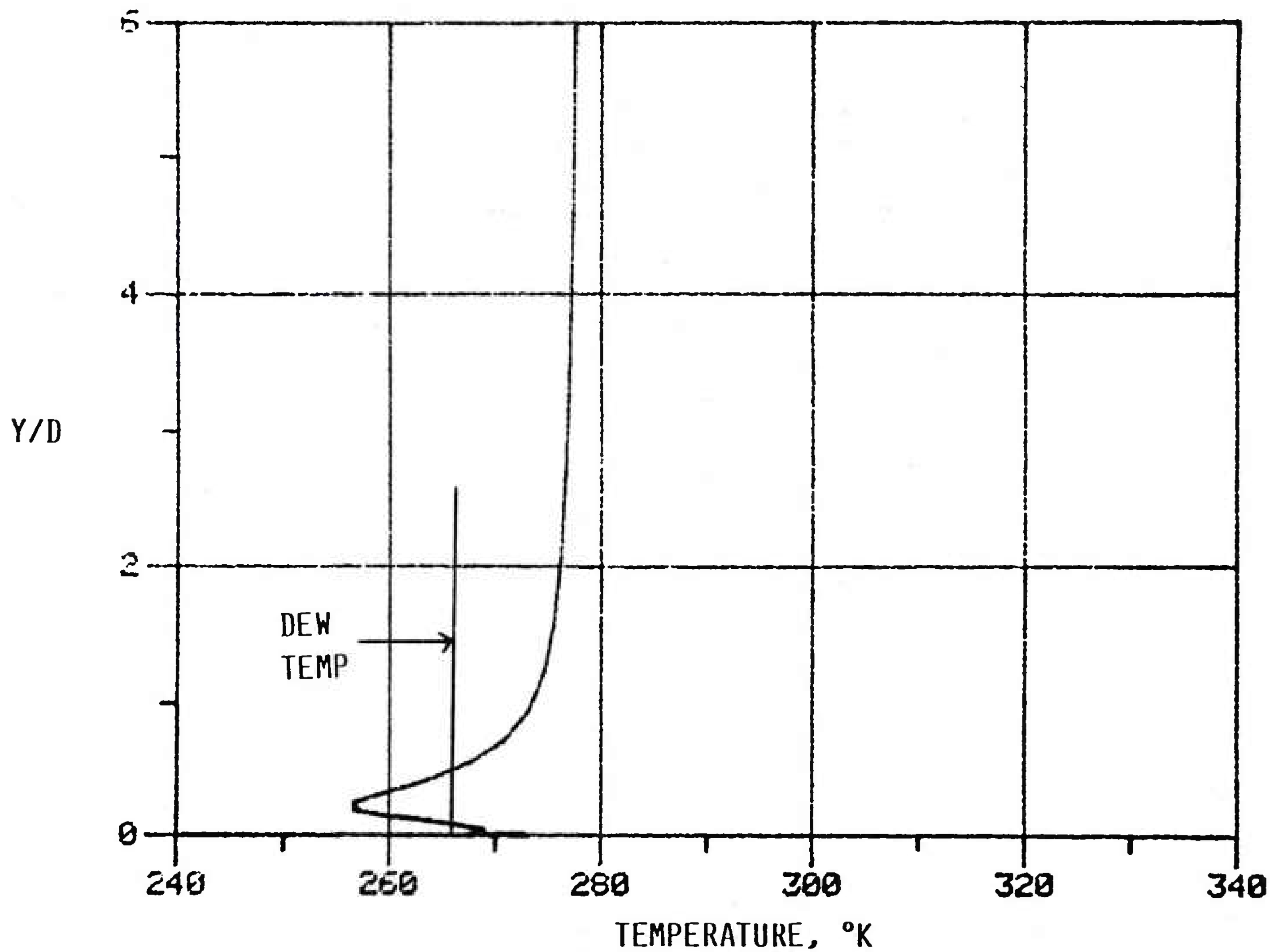


Figure 12. Temperature Profile, M = 0.9, T_∞ = 277K, T_W = 241K, X/D = 5.23

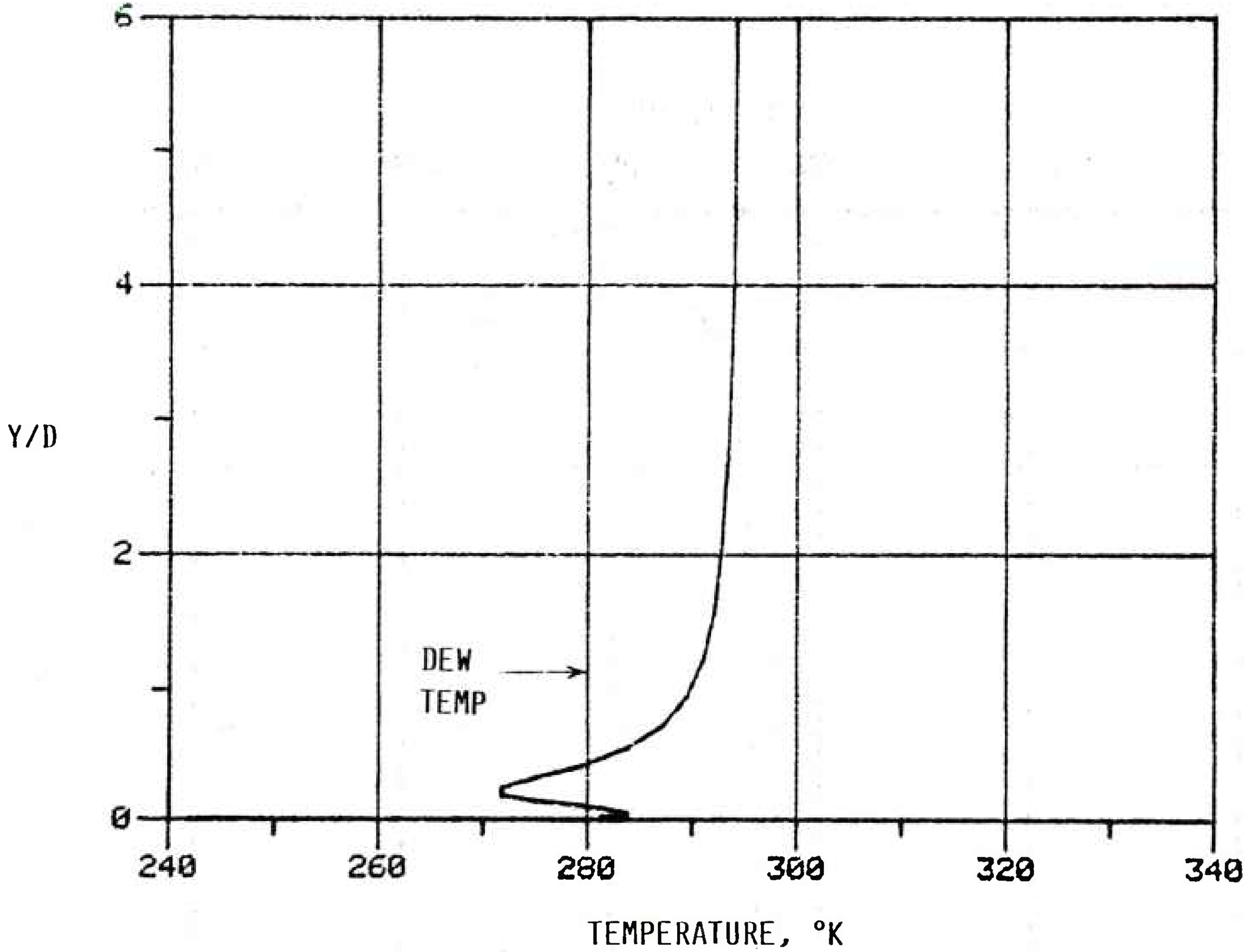


Figure 13. Temperature Profile, M = 0.9, T_∞ = 294K, T_W = 241K, X/D = 5.23

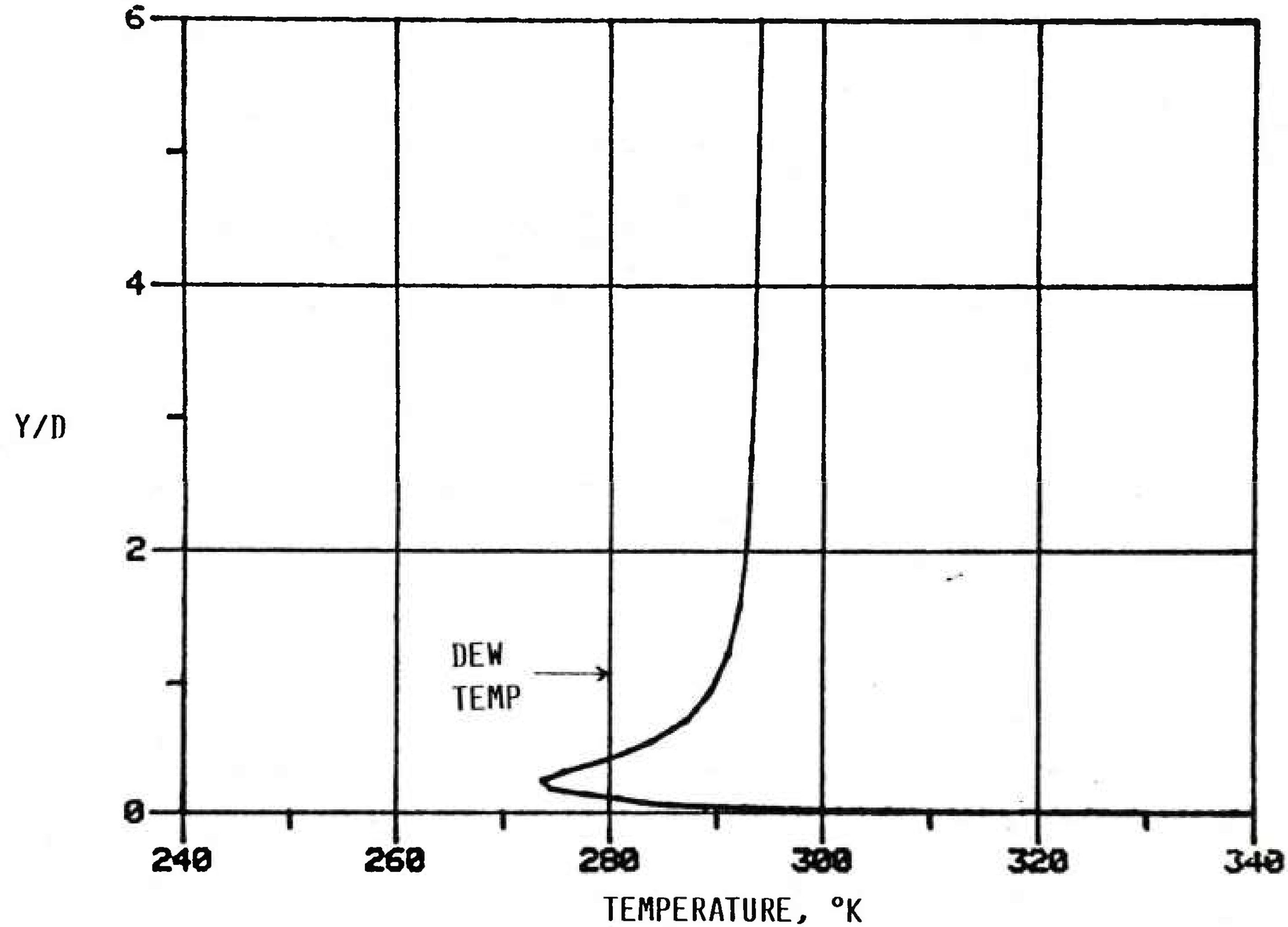


Figure 14. Temperature Profile, M = 0.9, T_∞ = 294K, T_w = 294K, X/D = 5.23

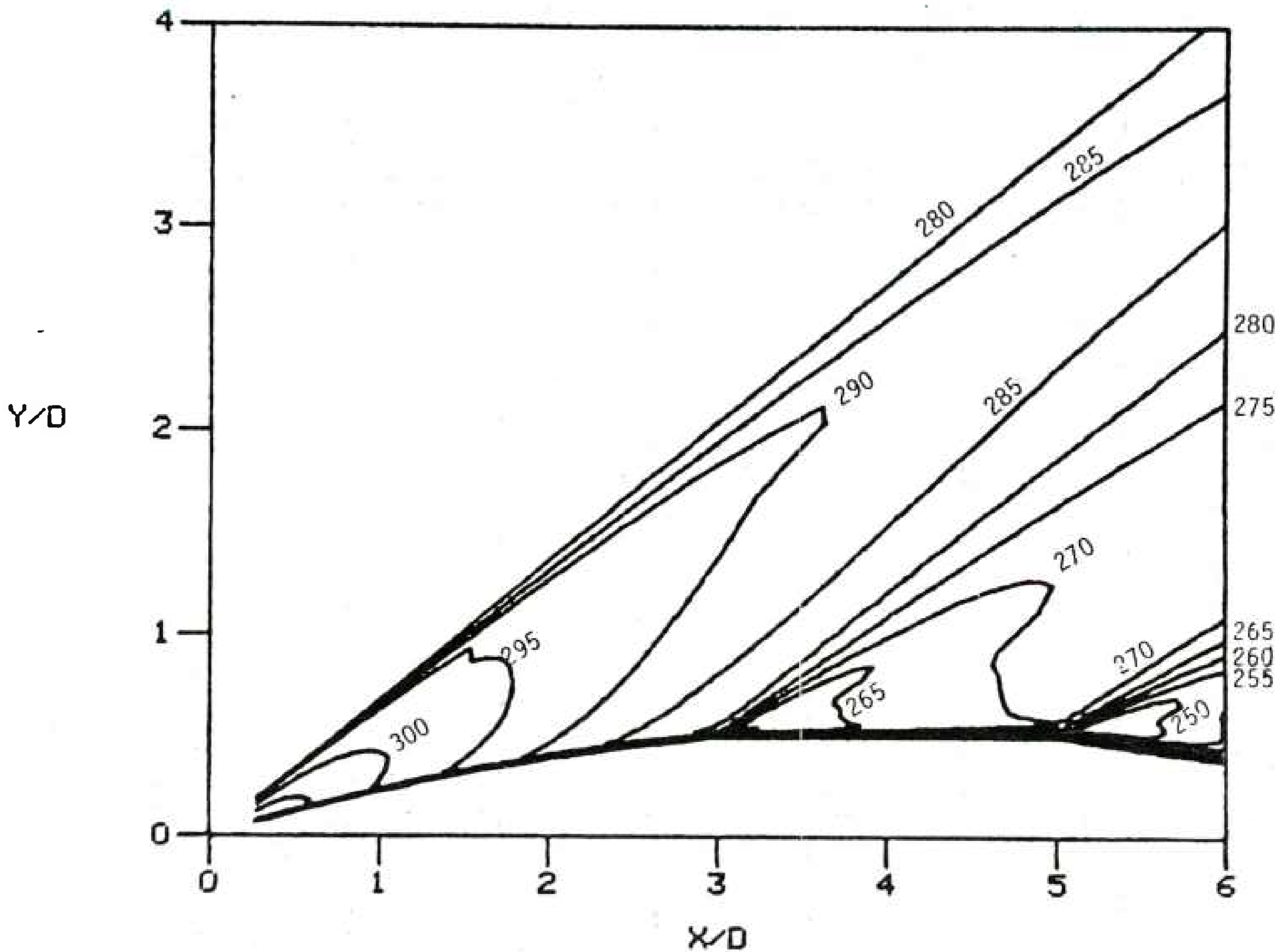


Figure 15. Static Temperature Contour Plot, M = 2, T_∞ = 277K, T_W = 241K, T_D = 266K

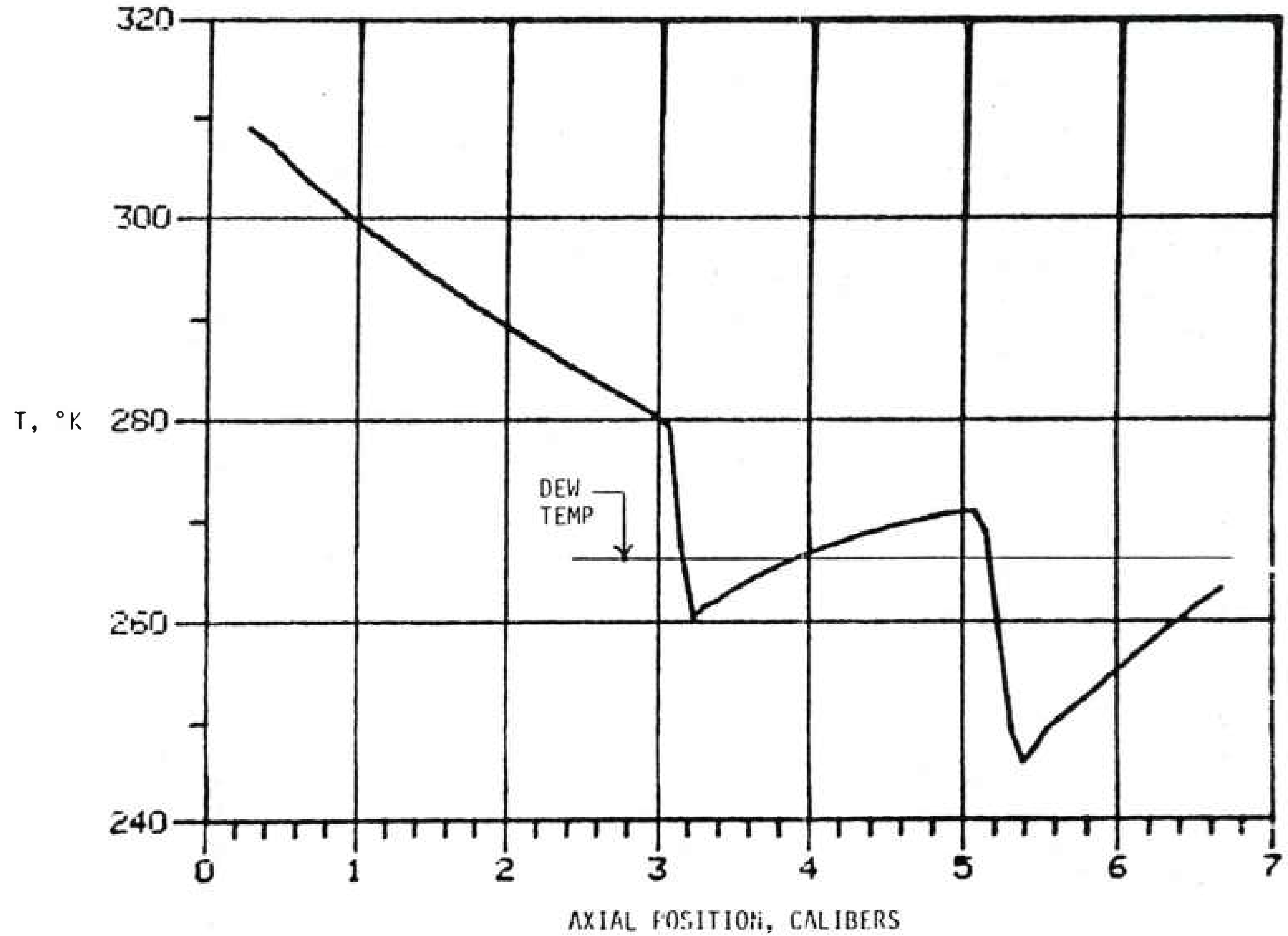


Figure 16. Longitudinal Temperature Distribution, M = 2, T_∞ = 277K, T_w = 241K,Y/D ≈ .1

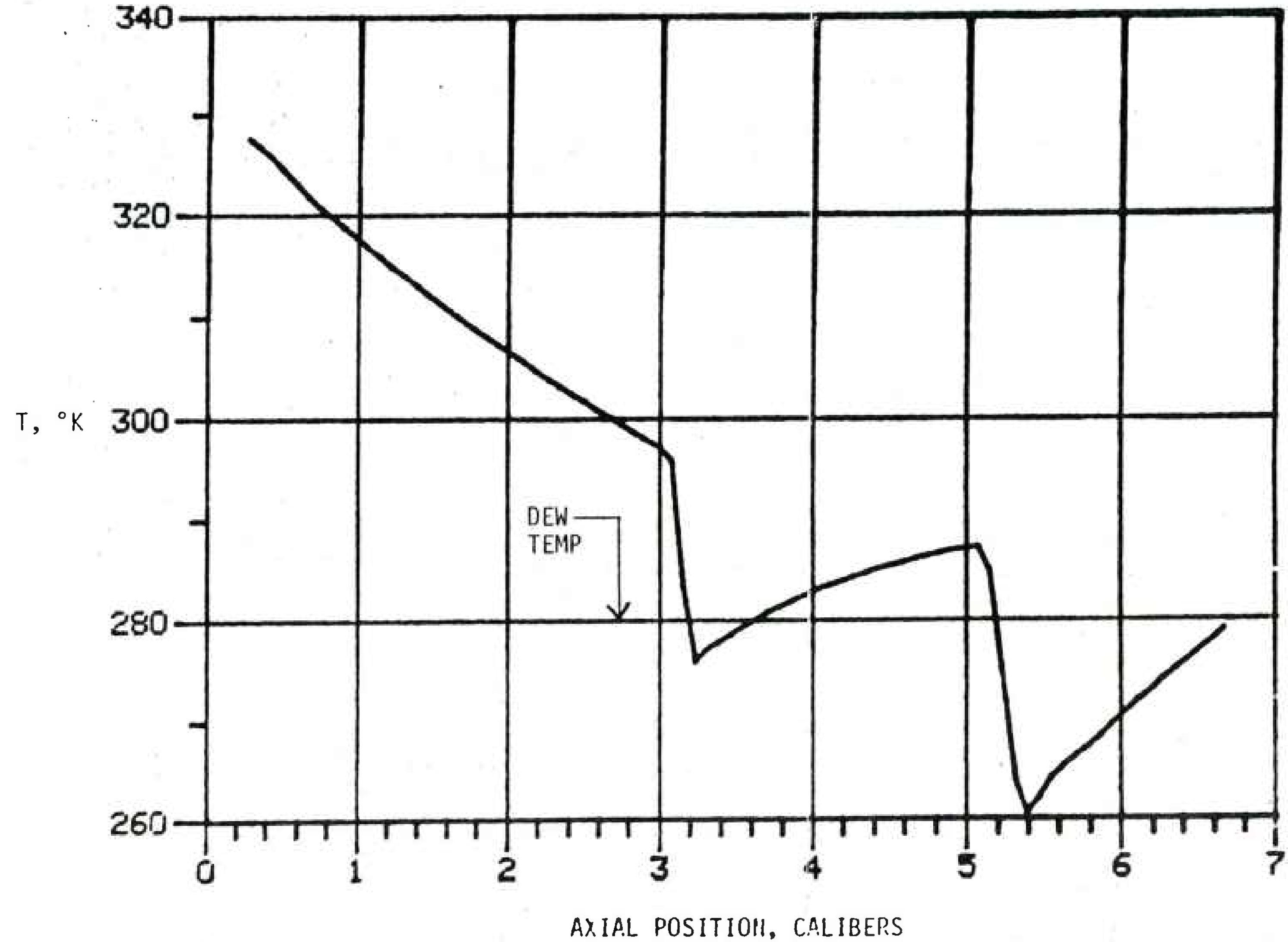


Figure 17. Longitudinal Temperature Distribution, M = 2, T_∞ = 294K, T_W = 241K, Y/D ≈ .1

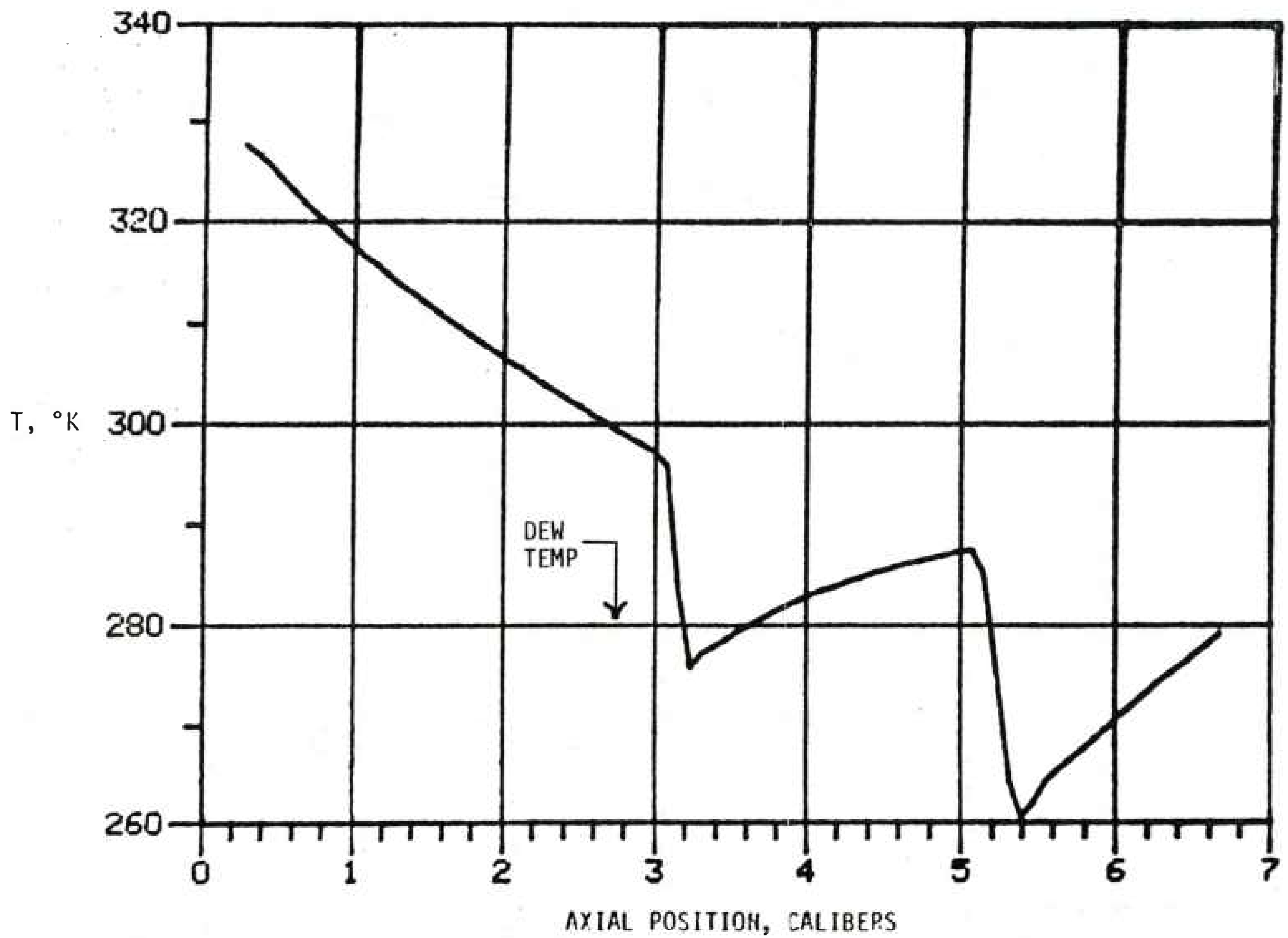


Figure 18. Longitudinal Temperature Distribution, M = 2, T_∞ = 294K, T_W = 294K, Y/D ≈ .1

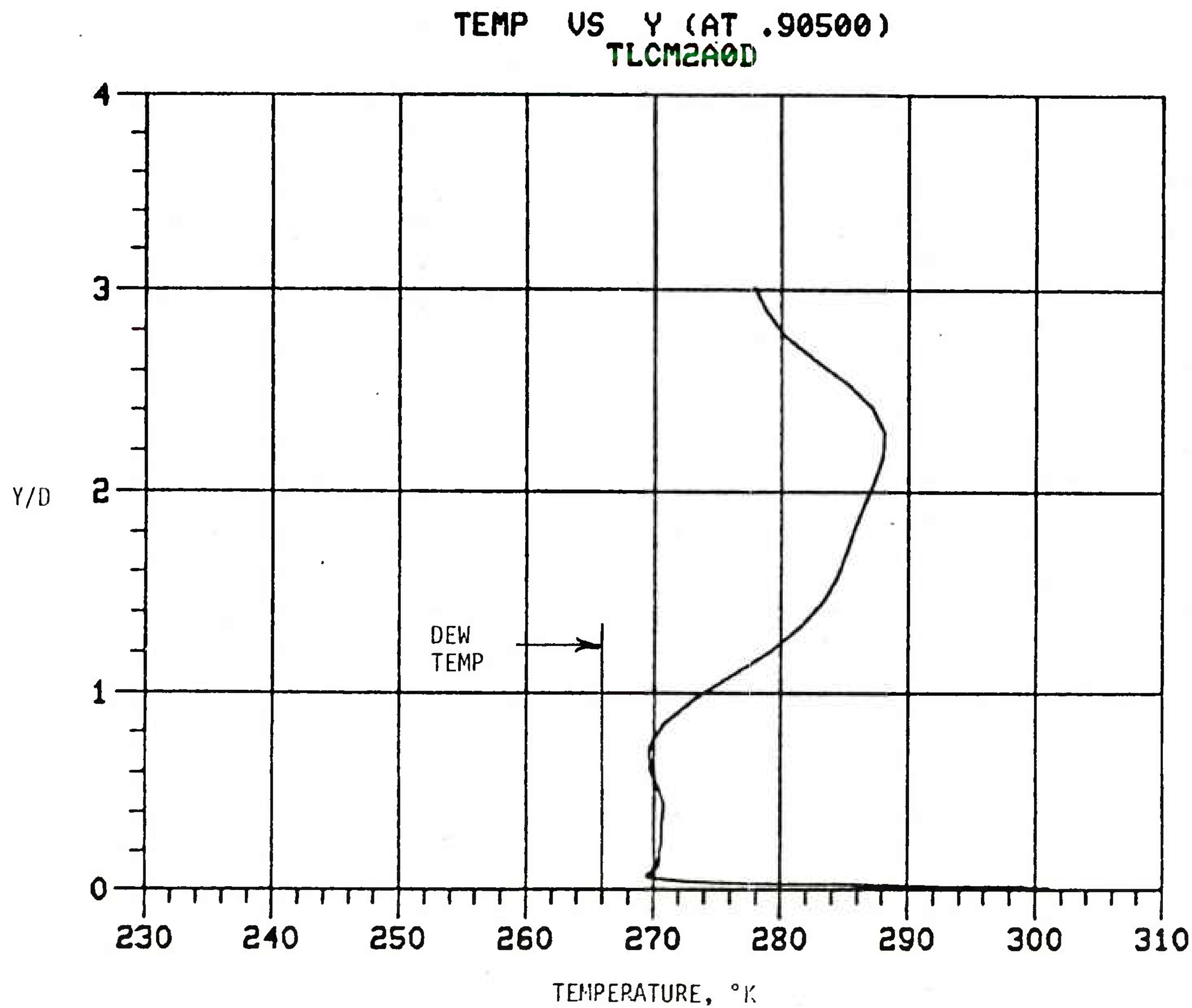


Figure 19. Temperature Profile, M = 2, T_∞ = 277K, T_W = 241K, X/D = 4.83

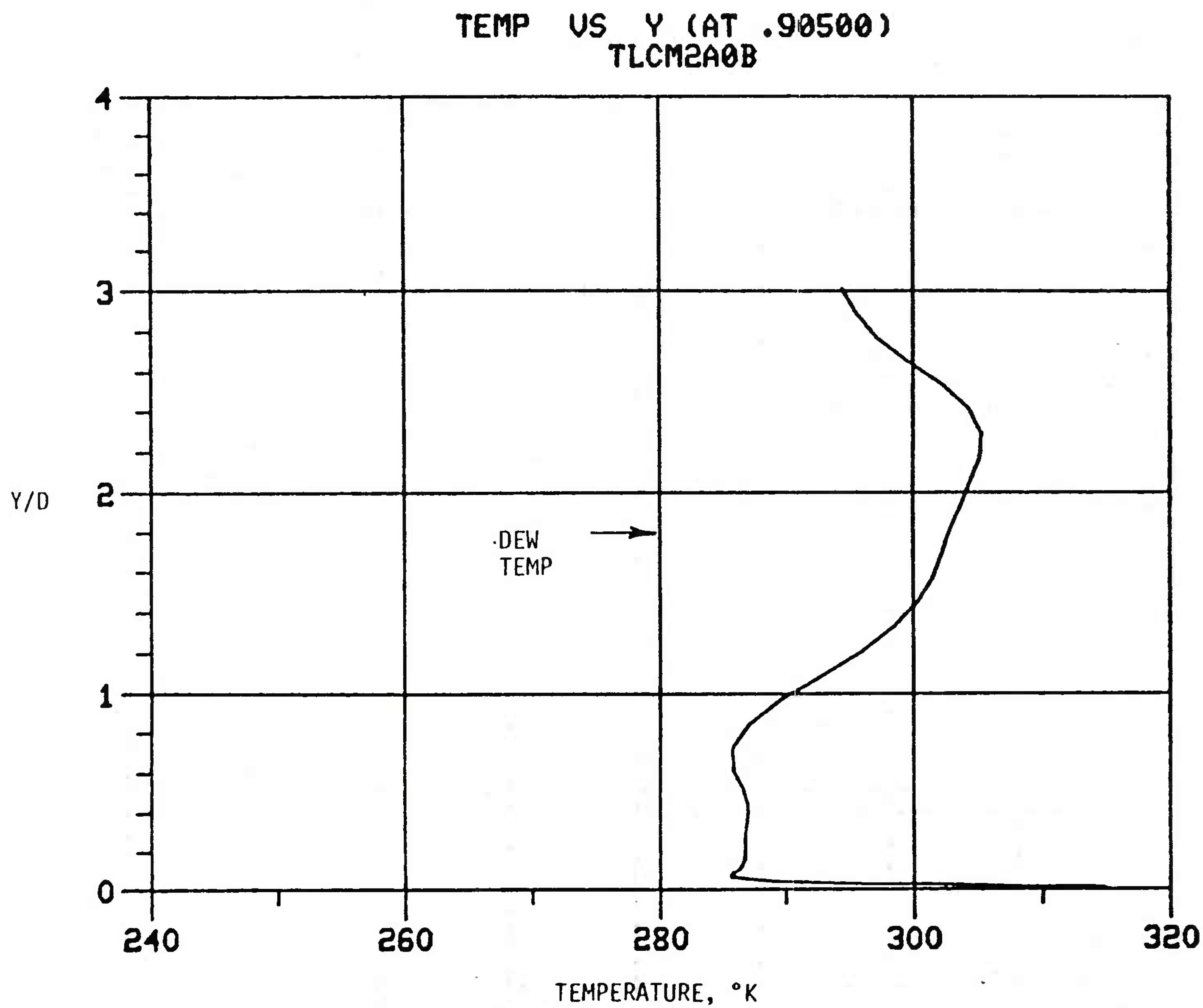


Figure 20. Temperature Profile, M = 2, T_∞ = 294K, T_w = 241K, X/D = 4.83

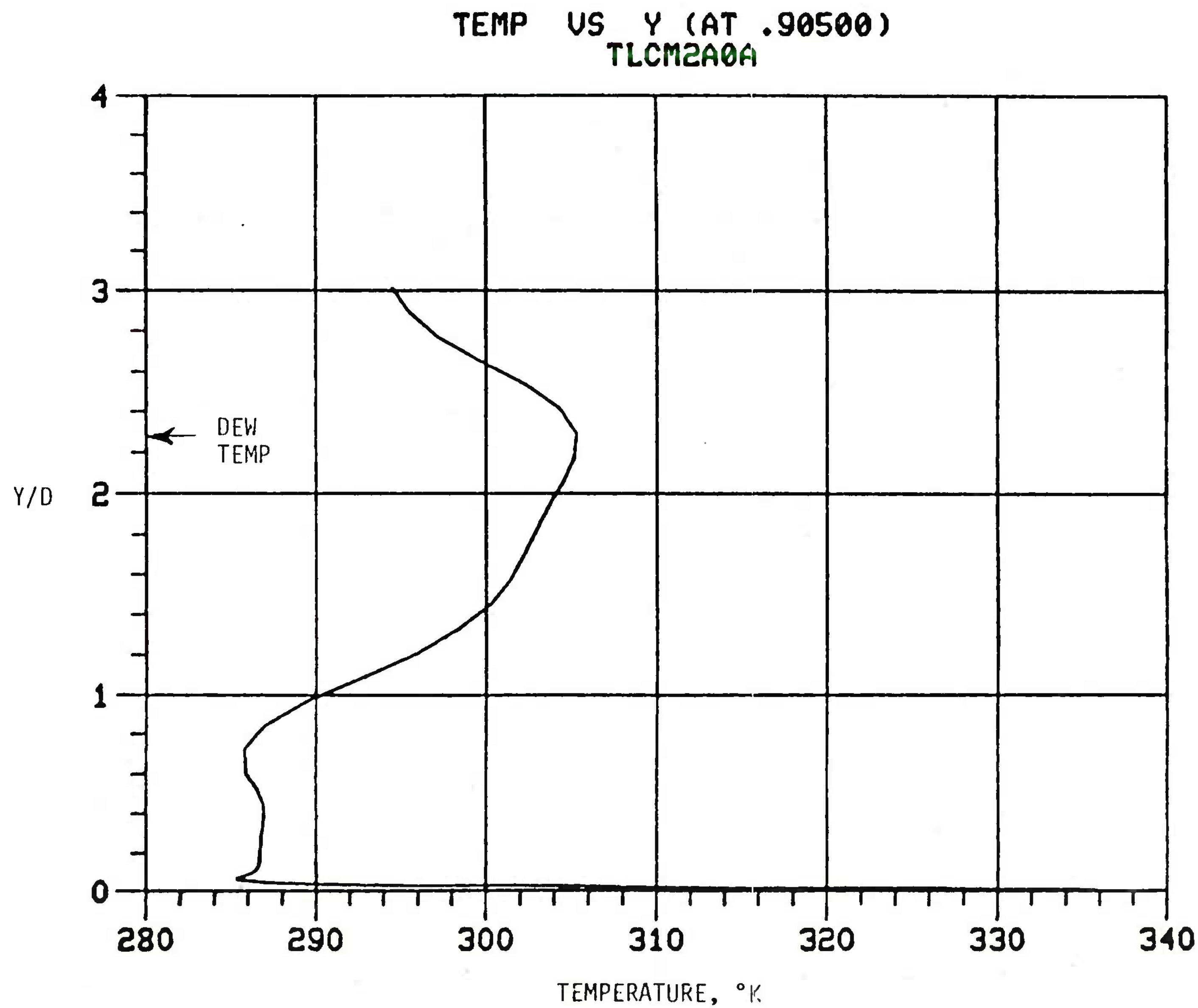


Figure 21. Temperature Profile, M = 2, T_∞ = 294K, T_W = 294K, X/D = 4.83

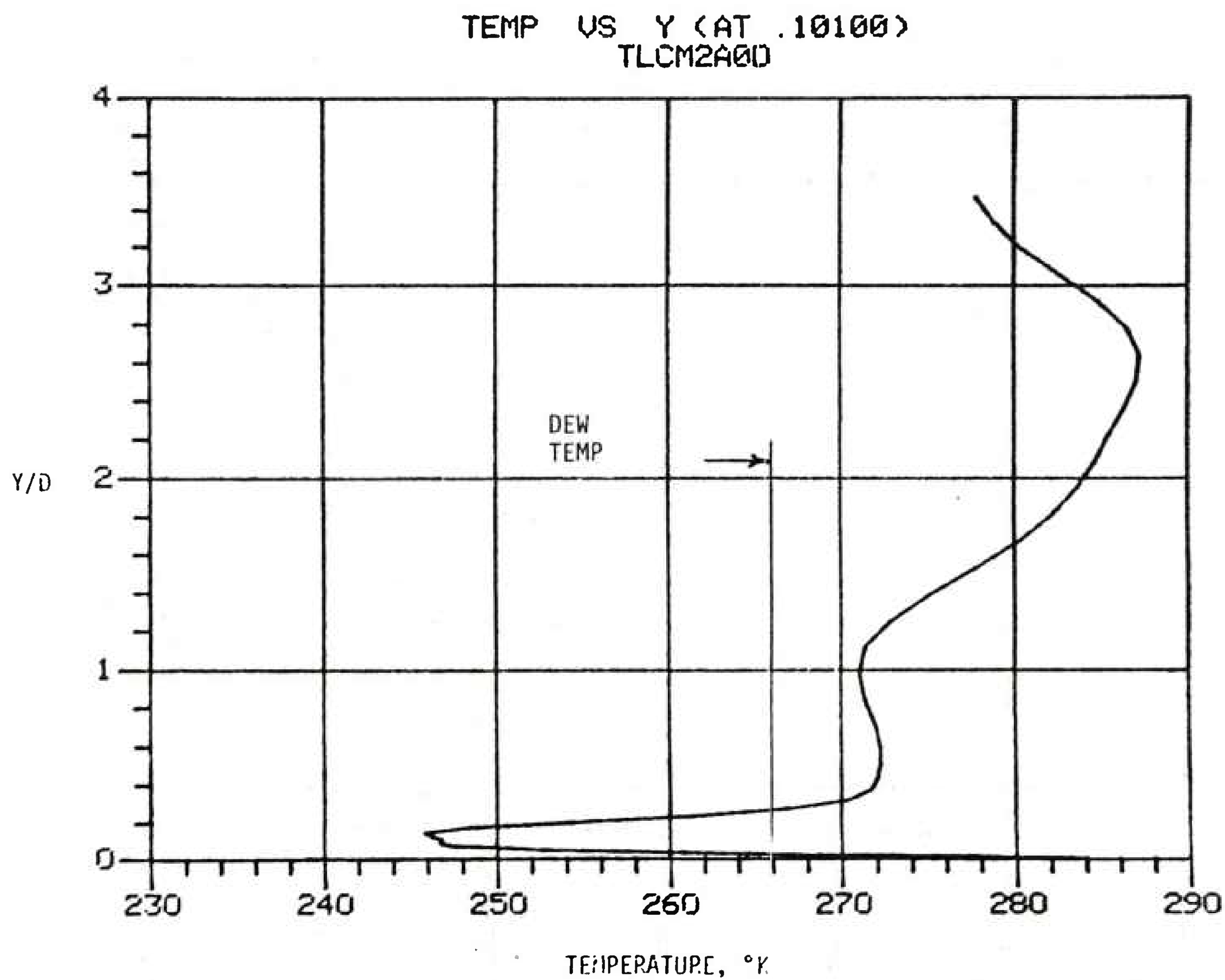


Figure 22. Temperature Profile, M = 2, T_∞ = 277K, T_W = 241K, X/D = 5.39

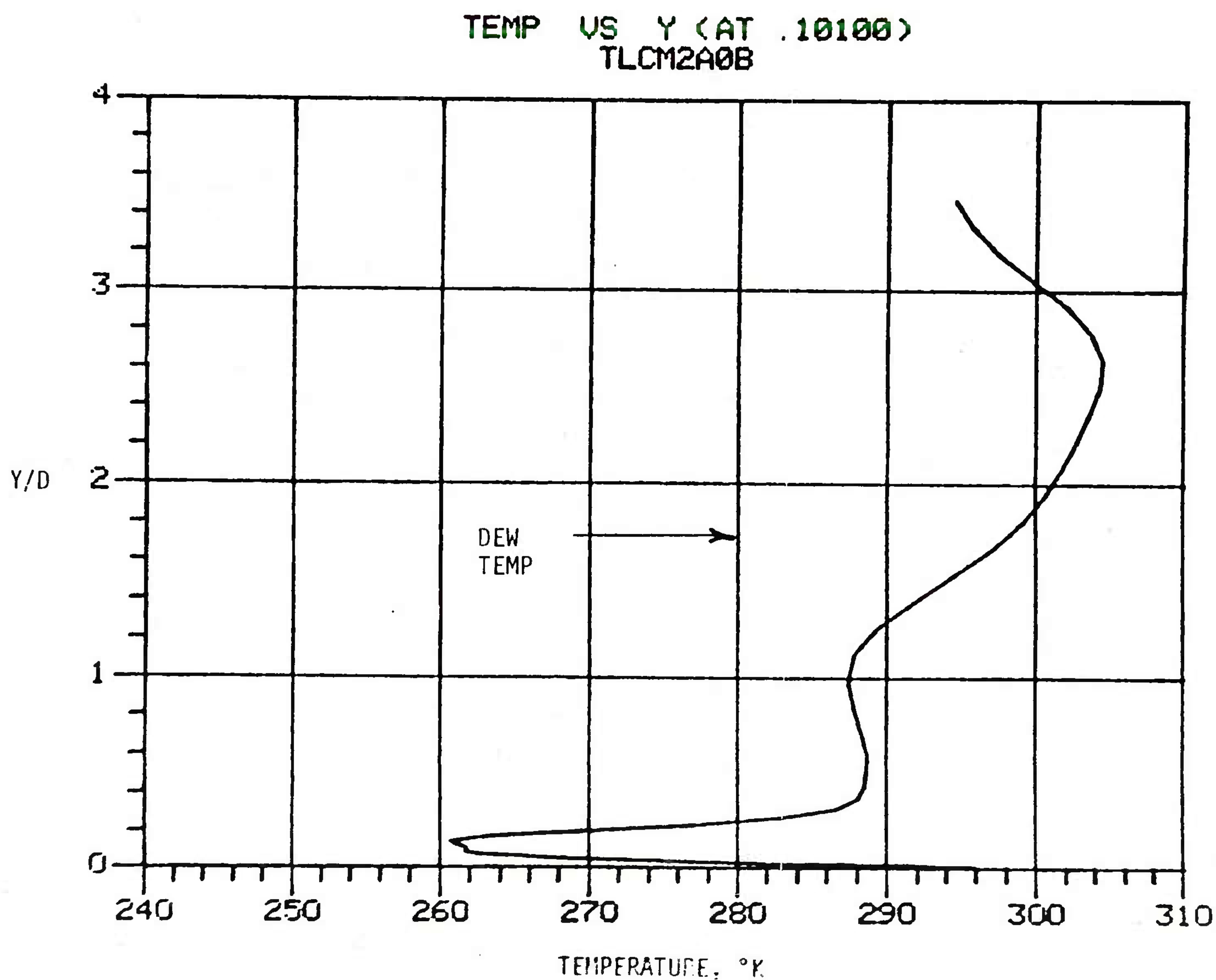


Figure 23. Temperature Profile, M = 2, T_∞ = 294K, T_W = 241K, X/D = 5.39

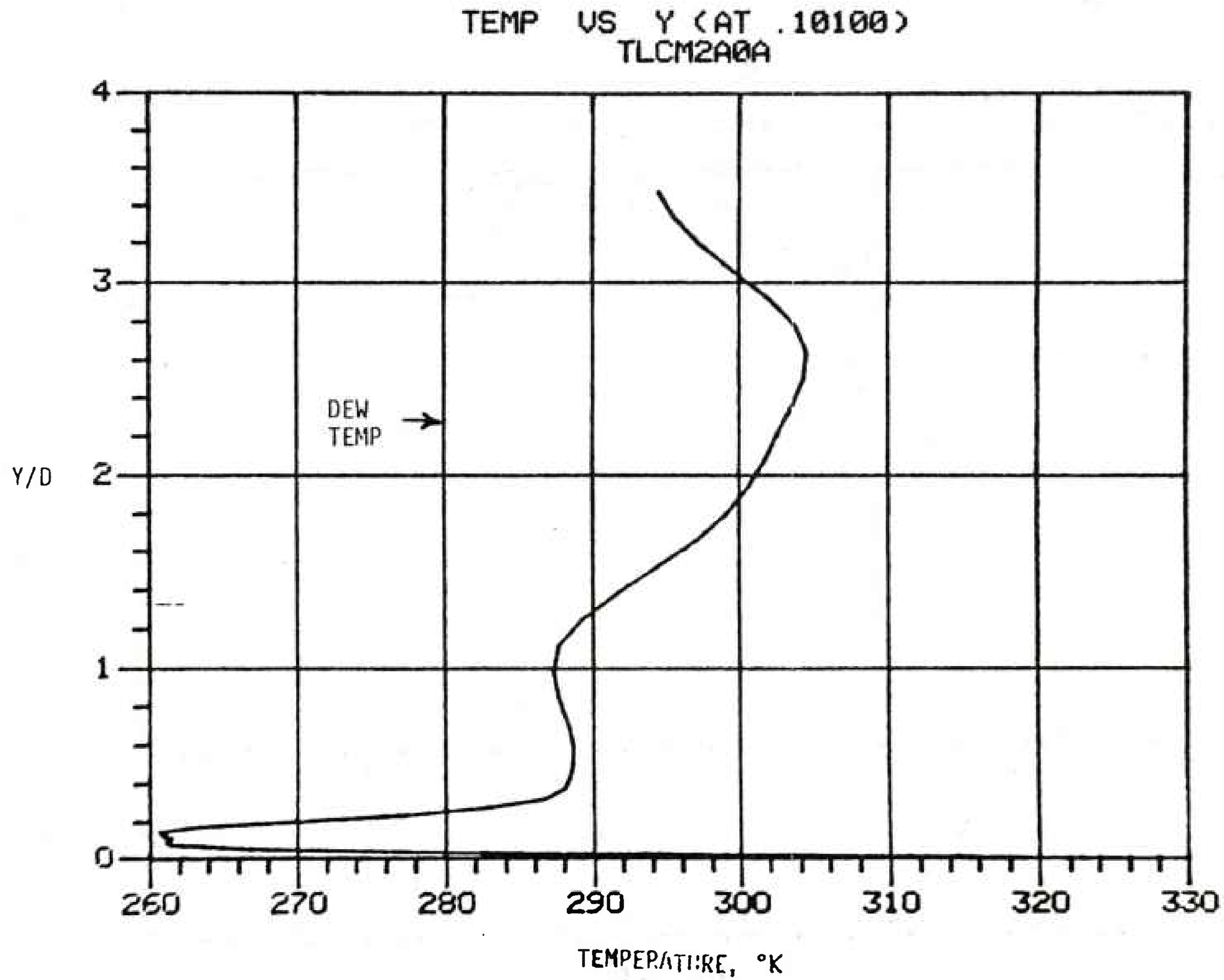


Figure 24. Temperature Profile, M = 2, T_∞ = 294K, T_w = 294K, X/D = 5.39

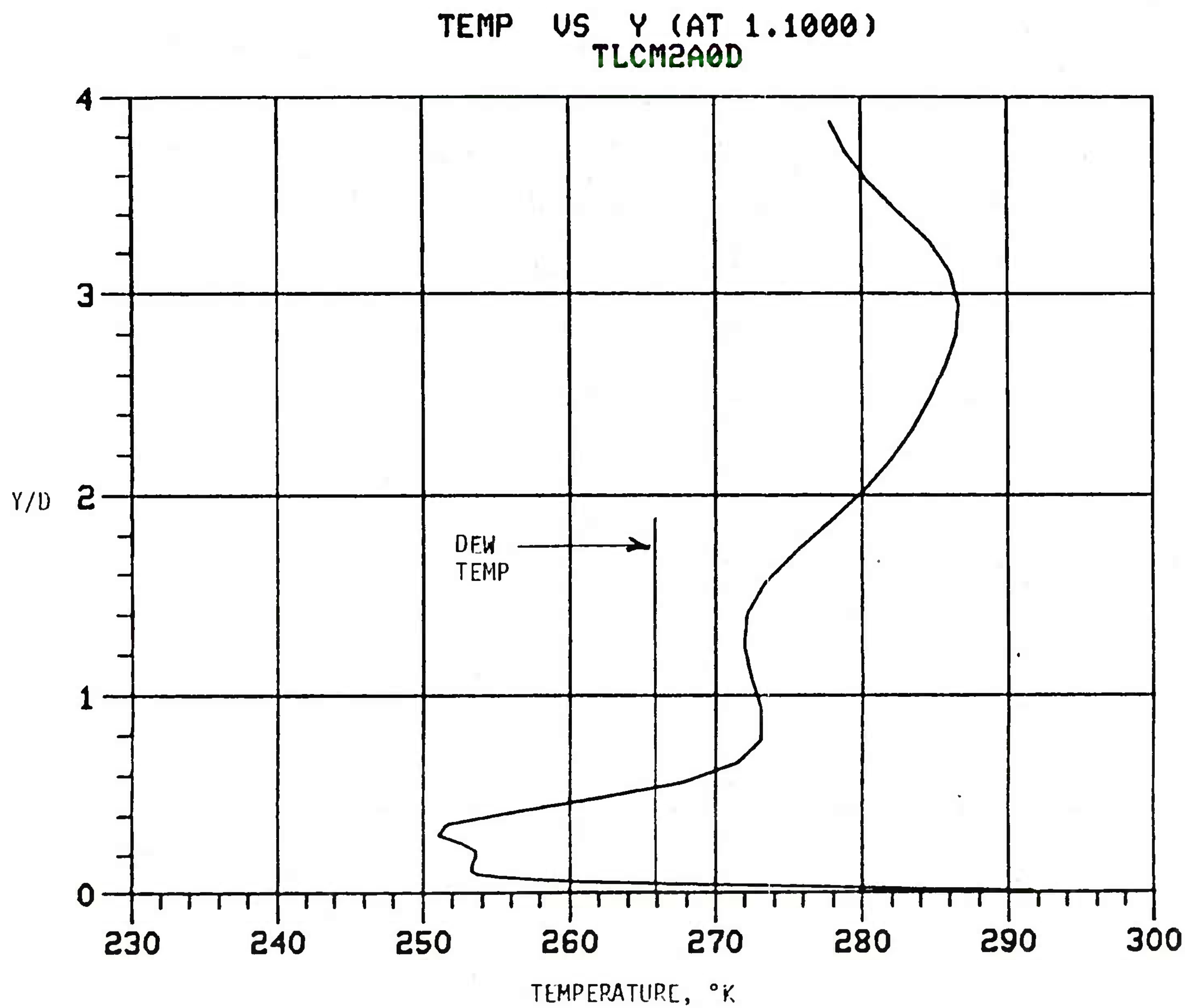


Figure 25. Temperature Profile, M = 2, T_∞ = 277K, T_W = 241K, X/D = 5.87

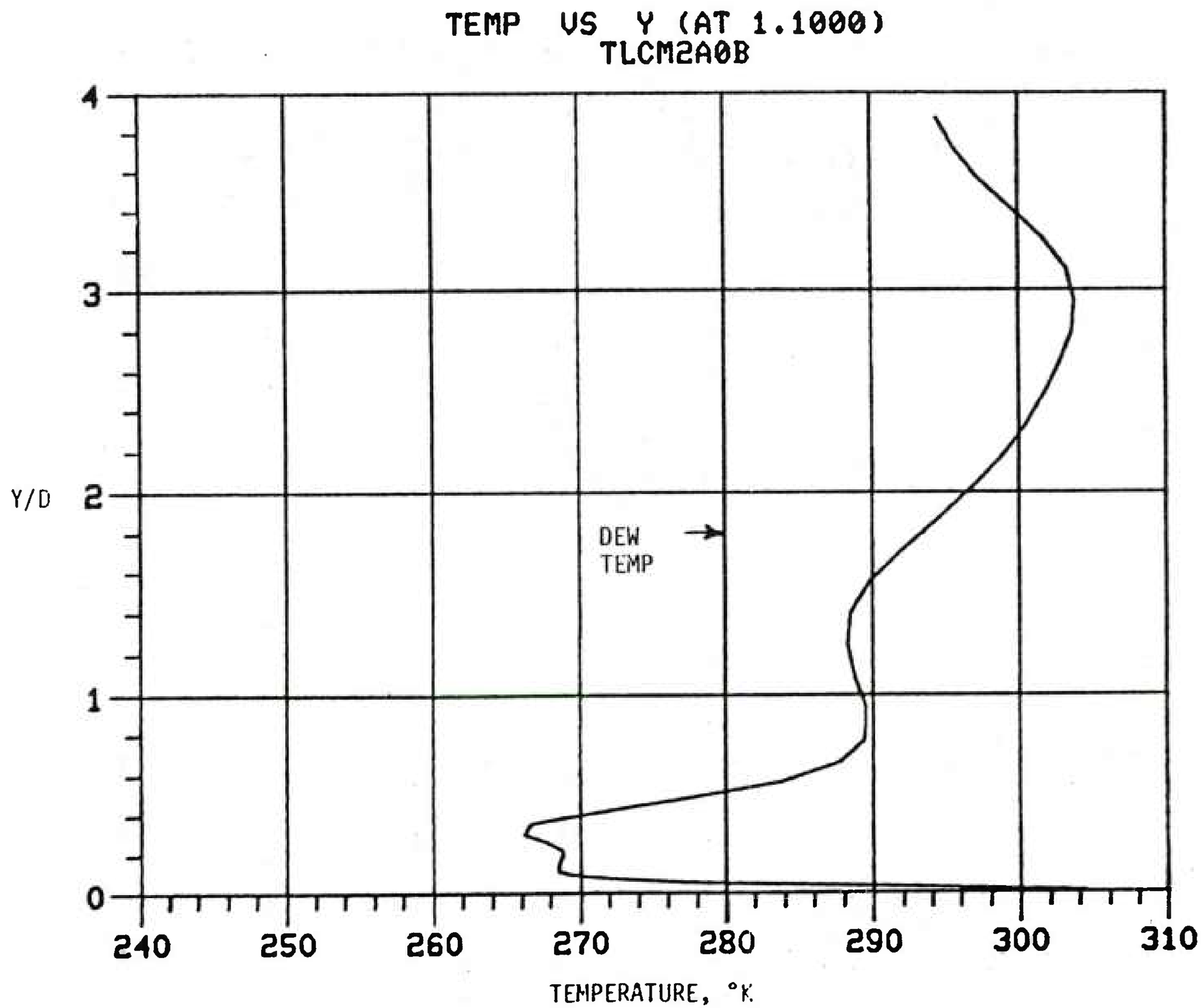


Figure 26. Temperature Profile, M = 2, T_∞ = 294K, T_w = 241K, X/D = 5.87

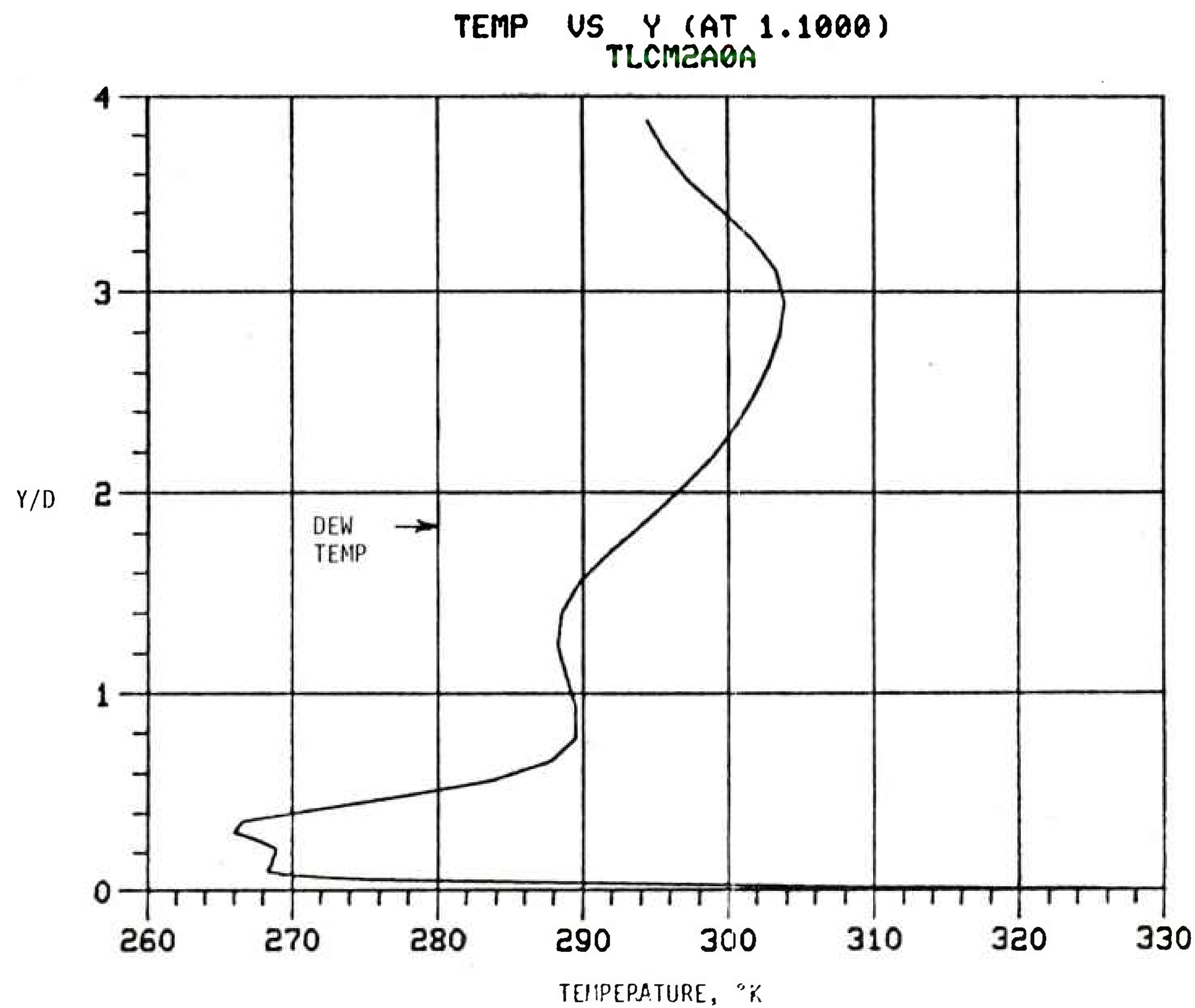


Figure 27. Temperature Profile, M = 2, T_∞ = 294K, T_W = 294K, X/D = 5.87

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